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INSIDE

How to talk to extraterrestrials

Supercharged space rockets

Mysterious radio signals from space

Visitors from outside our solar system

Are we alone in the Milky Way?

THE SEARCH FOR ALIEN LIFE

Science's latest insights on who's out there and how we might find them

SUMMER 2022

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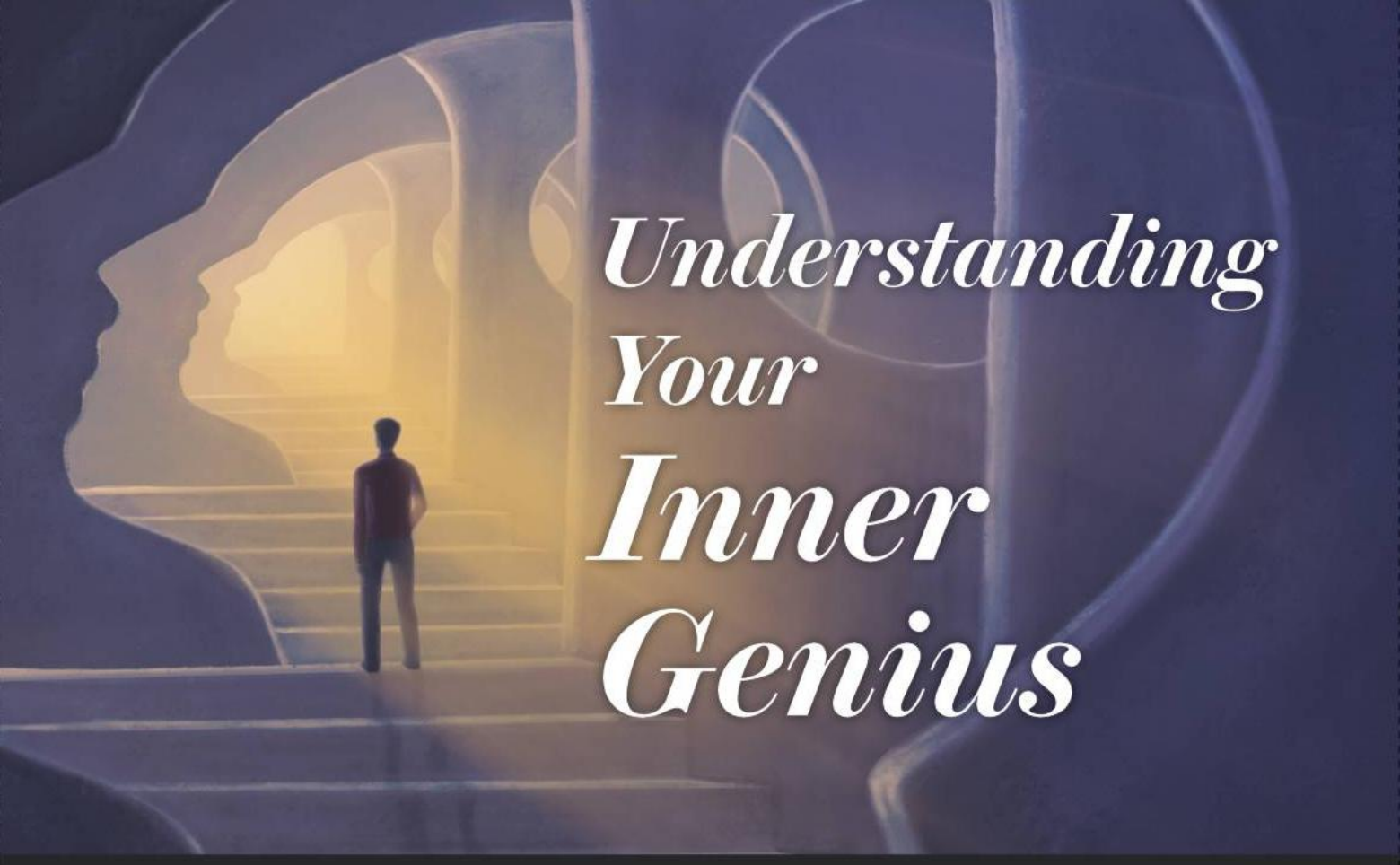

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FROM THE EDITOR

Are We Alone?

At a recent event about the latest science of exoplanets, former NASA Kepler mission astrophysicist Natalie Batalha redefined what it means to look into the night sky. Rather than seeing solitary stars peppered in space, she said, she now thinks of each point of light as its own solar system of orbiting planets. Astronomers estimate that there are some 100 billion to 200 billion galaxies in the universe—averaging 100 million stars apiece. The number of exoplanets out there is mind-boggling, each a potential cradle for life. Given the math, it seems impossible that we humans would be the only living things in the cosmos.

The variety of climates and conditions on these faraway bodies would be staggering. Even our own sister planet Venus is drastically different from Earth and demonstrates the difference 40 million miles can make—a cosmic stone's throw (*page 4*). Researchers are using such insights to intuit the conditions of planetary bodies light-years away (*page 30*) and are even looking for moons around exoplanets, which may have suitable conditions for life (*pages 12* and *20*).

To seek out new worlds, technology is advancing quickly. Boosted by the James Webb Space Telescope, launched at the end of 2021, the search for alien life over the next decade now has real depth (*page 34*). Next-gen enormous rockets coming soon promise space missions that can go farther and deploy more powerful telescopes (*page 38*). Privately funded scopes (*page 50*) and revolutionary observational techniques using our own sun as a gravitational lens (*page 53*) portend major advances in the near future.

Perhaps no other field of research has such a hold on the imagination. Recently spotted interstellar rocks (*page 60*) and meteors (*page 70*) spurred debate over their origins, as did a mysterious radio signal detected from the star Proxima Centauri, a mere four light-years away from Earth (*page 68*). If we do ever have convincing evidence that we've discovered extraterrestrial life, what is the best way to communicate that news to humanity (*page 73*)?

Looking for life off-Earth prompts interesting philosophical questions. If we use the chemistry of life's beginning on our own planet as a rubric, it might dictate (or limit) how we investigate life elsewhere (*page 80*). The universe may be teeming with unexpected chemical lifeforms that look very different from us (*page 88*). And then there's the matter of chance. As astrophysicist John Gribbin writes on page 106, a serendipitous chain of events had to occur—from the timing of our solar system's formation to our planet's distance from the sun—for organisms to spring up on Earth. It may well be that such conditions are actually rare. And even if alien civilizations are abundant, the universe is immense—beyond the scope of the human mind, certainly—and our cosmic backyards keep us far apart (*page 98*).

Legendary astronomer and science educator Carl Sagan was a firm believer that the cosmos is full of intelligent beings. He even more vehemently valued scientific reason and evidence and was known to say that extraordinary claims—even if they support your most wished-for dreams—require extraordinary evidence. Given his brand of skepticism, one would hope that he would be pleased about the latest tools we've built to determine if we are indeed alone. In the 1997 film *Contact,* based on the 1985 science-fiction novel written by Sagan about the discovery of an extraterrestrial radio signal, the main character, astronomer Ellie Arroway, says, "The universe is a pretty big place … so if it's just us, it seems like an awful waste of space."

Andrea Gawrylewski
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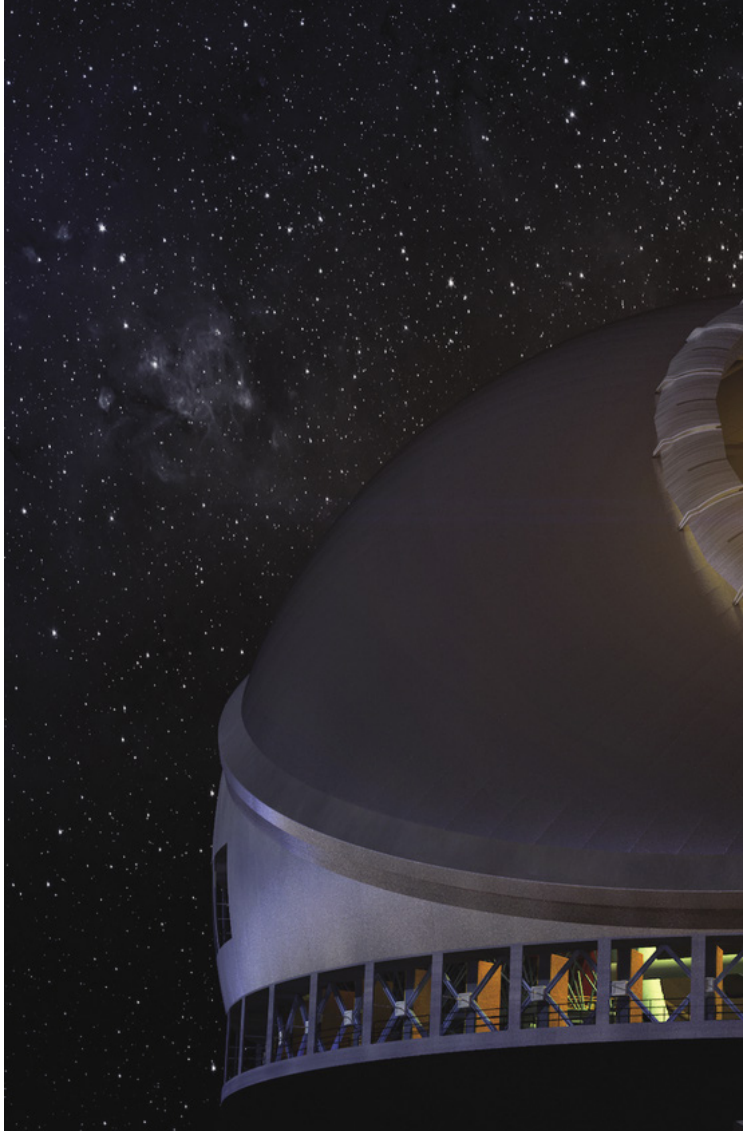

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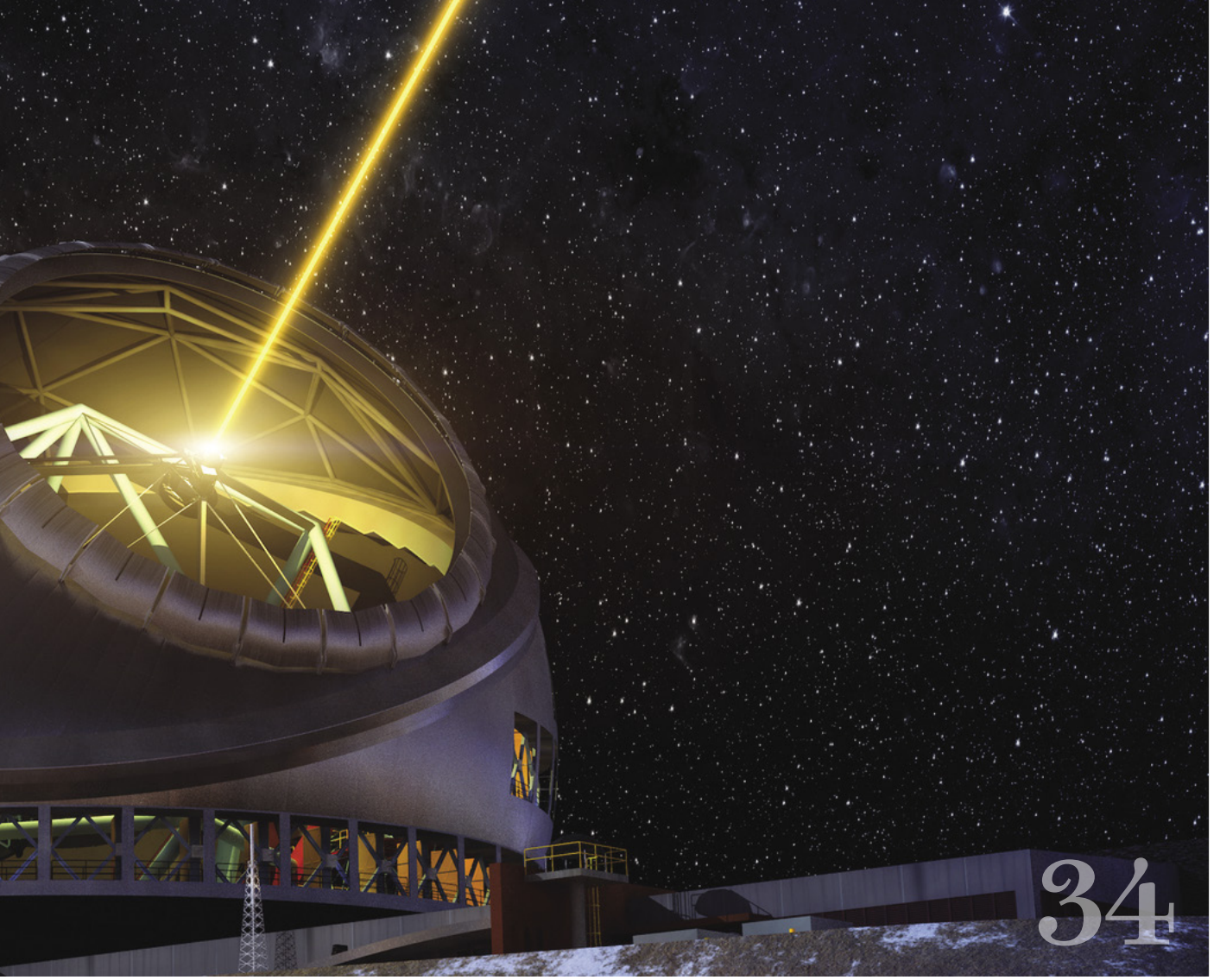

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Articles in this special issue are updated or adapted from previous issues of *Scientific American* and from ScientificAmerican.com.

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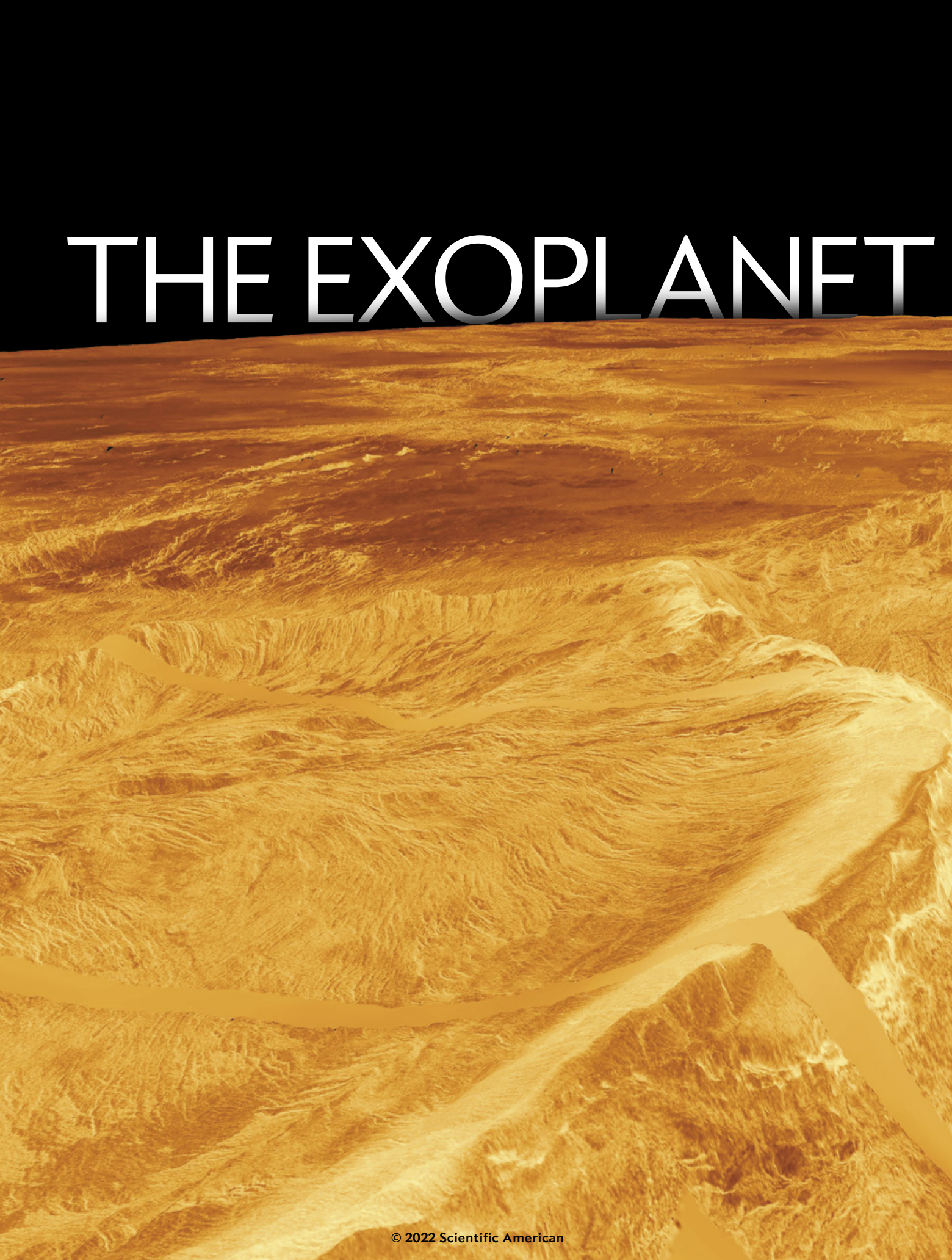
THE EXOPLANET



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What Venus can teach us about planets far beyond our own solar system

By M. Darby Dyar, Suzanne E. Smrekar and Stephen R. Kane

NEXT DOOR

RADAR DATA from the Magellan spacecraft was used to create this computer-generated view of Venus's Latona Corona and Dali Chasma.

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IN 1982 ALL ANYONE COULD TALK ABOUT IN THE PLANETARY SCIENCE DEPARTMENT at the Massachusetts Institute of Technology was the cancellation of NASA's latest flagship mission, the Venus Orbital Imaging Radar (VOIR). One of us (Dyar) was a graduate student there at the time. (The other two were still in college and elementary school.) Graduate students wept openly in the hallways, and veteran faculty shook their heads. The newly elected Reagan administration had enacted sweeping cuts to space exploration, and VOIR was one of the casualties.

Shortly afterward, though, scientists cobbled together plans for a bargain-priced spacecraft ($680 million) made of leftover hardware and, miraculously, saved the mission. In 1989 the Magellan orbiter launched on a reconnaissance mission to Venus, and by 1990 it was in orbit. Over the next five years the orbiter returned near-global radar images, gravity data and a topographic map of the second planet from the sun. It was the latest in a long line of Soviet and U.S. missions to our neighboring planet, but when Magellan plunged to Venus's surface in 1994, NASA's support for Venus spacecraft died with it. Since then, scientists have submitted more than 25 proposals for return missions to Venus, and although some of those received high rankings from review boards, none were approved until very recently. Decades-old data gathered by Magellan remained the foundation of Venus geoscience.

But planetary scientists never give up, and we have made progress in uncovering the secrets of this world nonetheless. Since Magellan, the European and Japanese space agencies have sent successful missions to Venus, leading to breakthroughs in understanding its atmosphere. Meanwhile scientists have been busy rewriting the textbooks on our sister planet by performing new analyses of Magellan data. We now think that volcanoes are rampant on Venus, and we have even found hints of the start of plate tectonics, which scientists think is critical for a planet's habitability. New theoretical models also suggest Venus may have had liquid water on its surface until relatively late in its history—meaning that it may have been hospitable to life much longer than we once thought.

All of this coincides with another stunning development in astronomy: the discovery of thousands of exoplanets in other solar systems, many of them roughly the same size and distance from their stars as Venus. Anything we learn about the planet next door could teach us about these distant, inaccessible worlds. In particular, if we can figure out whether and when Venus may have had the conditions to host life, we will know more about the likelihood of finding living beings on the plethora of Venus-like bodies throughout the Milky Way.

EXOPLANET ANALOGUE

MOST OF THE EXOPLANETS discovered so far were found using the transit method, in which astronomers watch stars for telltale brightness fluctuations that occur as orbiting worlds pass in front of them. With this technique, we can measure a distant planet's size, but size tells us only so much. After all, if an extraterrestrial observer were to look at our solar system using the transit method, Venus and Earth would appear almost identical. Yet Venus is forbidding to life, whereas Earth has been continually habitable for the past four billion years.

We can further differentiate between similarly sized planets by measuring their distances from their stars. The "habitable zone" is the region around a star where a rocky planet could have liquid water on its

NASA/JPL (*preceding pages*)

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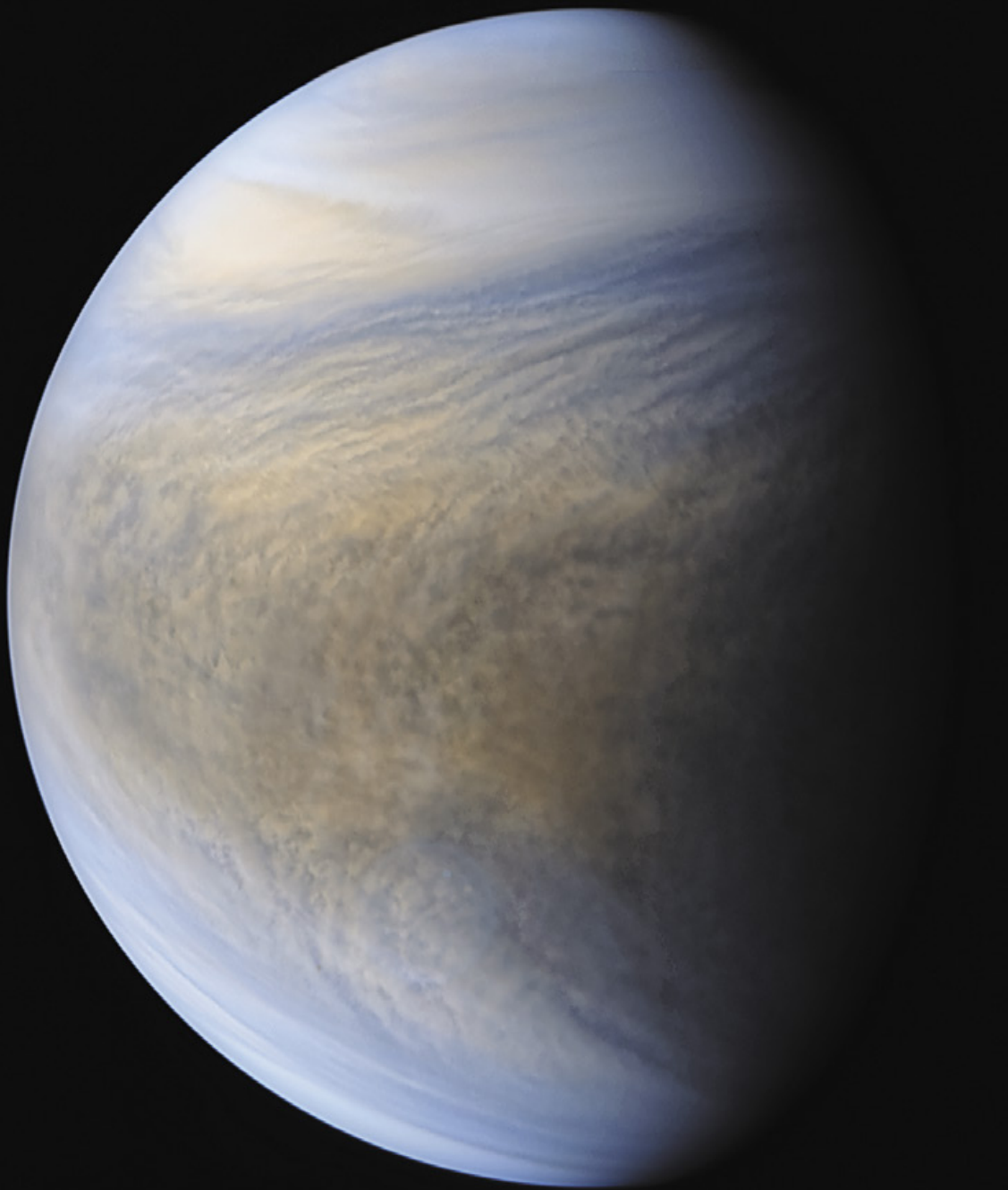

JAXA/ISAS/DARTS/Damia Bouic

VENUS'S ATMOSPHERE, as seen in this composite image from data taken by Japan's Akatsuki spacecraft, contains thick clouds of sulfuric acid.

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surface. Earth, obviously, is in this zone. Venus, we think, used to be in this zone—for quite a while, in fact. Yet the boundaries of the habitable zone move outward with time as the sun's luminosity increases with age. Venus is now outside this range and occupies what we call the "Venus zone," where surface conditions are so hot that a planet is likely to have a runaway greenhouse atmosphere that would boil its oceans away.

We have never had better reasons to send a new major mission to the oft-ignored second planet from the sun.

Venus and Earth formed under very similar conditions—including those that gave Earth its oceans. Comet impacts probably brought ice to the surface of both planets. The solar wind (charged particles gushing off the sun) most likely implanted a thin layer of hydrogen ions on the surfaces of both. And when Venus and Earth were protoplanets building up from the primordial dust disk that circled the sun, both collected hydrogen and other volatiles, chemicals that can easily boil away. Simulations of early Venus show that the planet's surface may have had liquid water earlier than Earth and that water might have been there until about a billion years ago.

The fact remains, though, that Venus is now forbiddingly inhospitable. What happened? Does Venus represent the end state for all habitable planets, or is it merely one of many ways that planets of this size can turn out? These are some of the major questions we want to go back to Venus to answer.

SHROUDED SURFACE

OUR KNOWLEDGE OF VENUS is limited in part by the immense difficulty of seeing through the planet's thick, noxious atmosphere. High up, clouds of sulfuric acid shroud the world. On the ground, the air pressure is comparable to the water pressure 3,000 feet below the surface of Earth's oceans. The atmosphere there is so dense that its main constituent, carbon dioxide, acts as a supercritical fluid, with properties midway between a gas and a liquid.

Scientists think this atmosphere was once Earth-like. Unlike our world, though, Venus now lacks a magnetic field to repel the solar wind. We think that over the eons, the solar wind eliminated the planet's water by dissociating it into hydrogen and oxygen ions and carrying them off into space. Without surface water to dissolve the carbon dioxide and other gases constantly escaping from the interior, these chemicals accumulated in the atmosphere. Because of the greenhouse effect of this atmosphere, surface temperatures on Venus are nearly 800 degrees Fahrenheit higher than on Earth—hot enough to make rocks glow.

The only data we have from the surface of Venus were collected by the four Soviet Venera landers that touched down in the 1970s and 1980s. These probes survived for only a few minutes on the planet's brutal surface, but in that brief time they gathered and sent back rough measurements of the chemical composition there. Beyond those readings, our knowledge of the surface mineralogy rests solely on controversial interpretations of radar measurements made by Magellan and our limited knowledge of probable chemical reactions between the planet's rocks and atmospheric gases under Venusian conditions.

Researchers have found that it is possible to map the minerals on Venus from orbit by looking through several "windows" in the electromagnetic spectrum where visible light escapes absorption by carbon dioxide in the atmosphere. Serendipitously, these windows coincide with critical regions for identifying the typical planetary minerals olivine and pyroxene, offering hope that we could finally determine the basic ingredients of Venus. Europe's Venus Express spacecraft, which orbited Venus from 2006 to 2014, used one of these windows to produce the first map of heat radiating from the planet's surface over much of the southern hemisphere. This map includes spectral features—peaks and dips in light and heat—that can identify minerals on the ground.

The map also identifies many hotspots—areas emitting so much heat that the most likely explanation is recent volcanism. This is an exciting find because it shows that unlike the moon, which has long been silent, and Mars, where modern volcanism has been isolated at best, Venus is still active—and that discovery has implications for the planet's suitability for life.

PLATE TECTONICS

ON EARTH, volcanism is usually associated with plate tectonics—the shifting and sliding of large pieces of crust responsible for most of the geologic features on our planet. Plate tectonics is also behind the long-term climate cycles, occurring over periods of around 100 million years, that enabled life to arise on Earth. Plate tectonics formed new crust at Earth's mid-ocean ridges and allowed layers of its crust to sink into the mantle—two processes that enabled our planet to lose its internal heat and cool to a point where life could arise. Tectonics also released volatile chemicals such as water, carbon dioxide and sulfur dioxide from deep within Earth out into the atmosphere and cycled volatiles back into the mantle when plates slipped underneath other plates.

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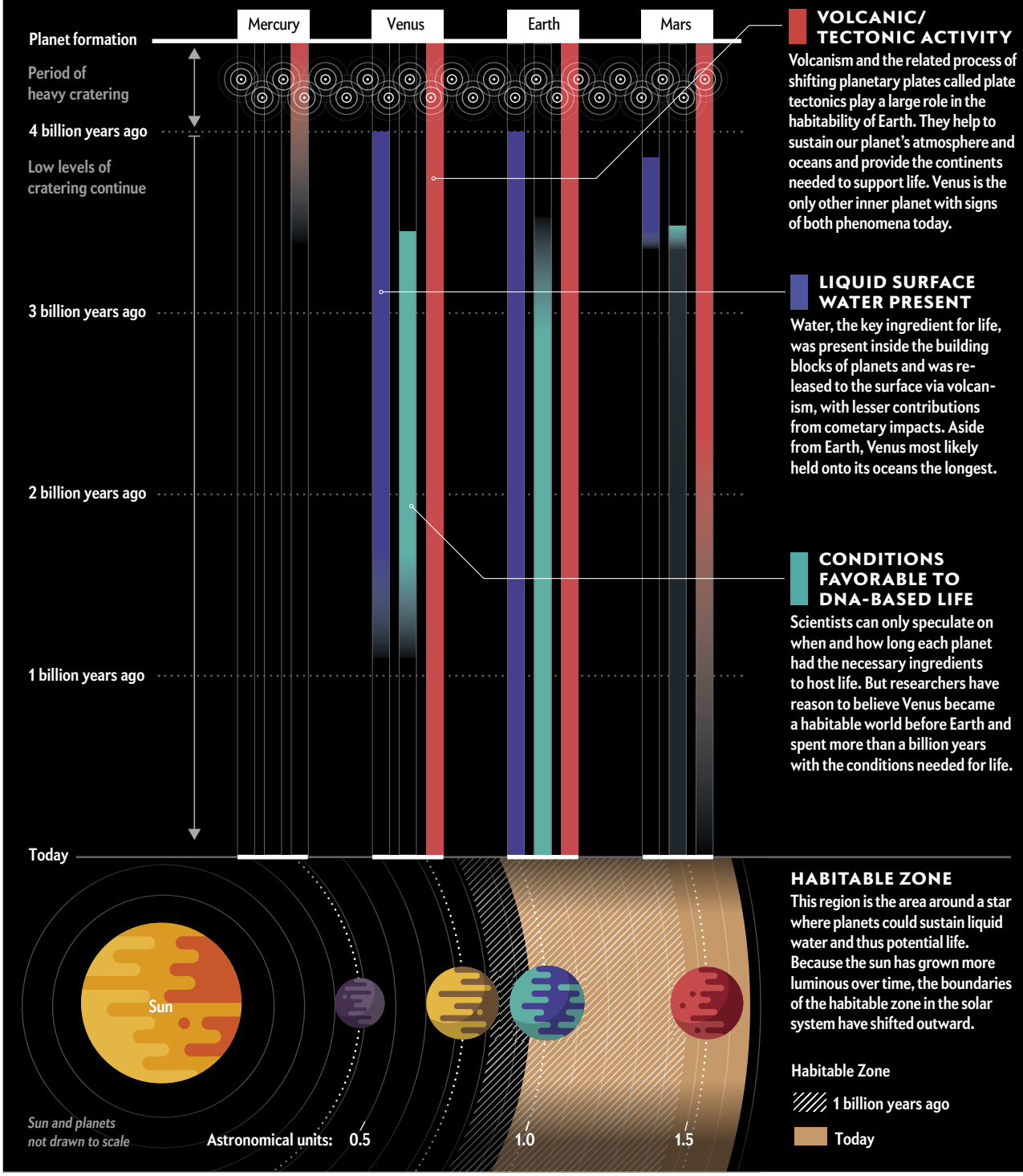
Planetary Comparisons

What makes a planet habitable? This is one of the biggest questions in astronomy. Earth and Venus started out quite similar, but now one is a bastion of life and the other an inhospitable wasteland. By studying the development of volcanism, plate tectonics and other conditions on Venus, scientists hope to understand why the planet evolved as it did and whether it can teach us about the prospects for life on the many Venus-like exoplanets throughout the Milky Way.



VOLCANIC/ TECTONIC ACTIVITY

Volcanism and the related process of shifting planetary plates called plate tectonics play a large role in the habitability of Earth. They help to sustain our planet's atmosphere and oceans and provide the continents needed to support life. Venus is the only other inner planet with signs of both phenomena today.

LIQUID SURFACE WATER PRESENT

Water, the key ingredient for life, was present inside the building blocks of planets and was released to the surface via volcanism, with lesser contributions from cometary impacts. Aside from Earth, Venus most likely held onto its oceans the longest.

CONDITIONS FAVORABLE TO DNA-BASED LIFE

Scientists can only speculate on when and how long each planet had the necessary ingredients to host life. But researchers have reason to believe Venus became a habitable world before Earth and spent more than a billion years with the conditions needed for life.

HABITABLE ZONE

This region is the area around a star where planets could sustain liquid water and thus potential life. Because the sun has grown more luminous over time, the boundaries of the habitable zone in the solar system have shifted outward.

Habitable Zone
1 billion years ago
Today

Graphic by Tiffany Farrant-Gonzalez

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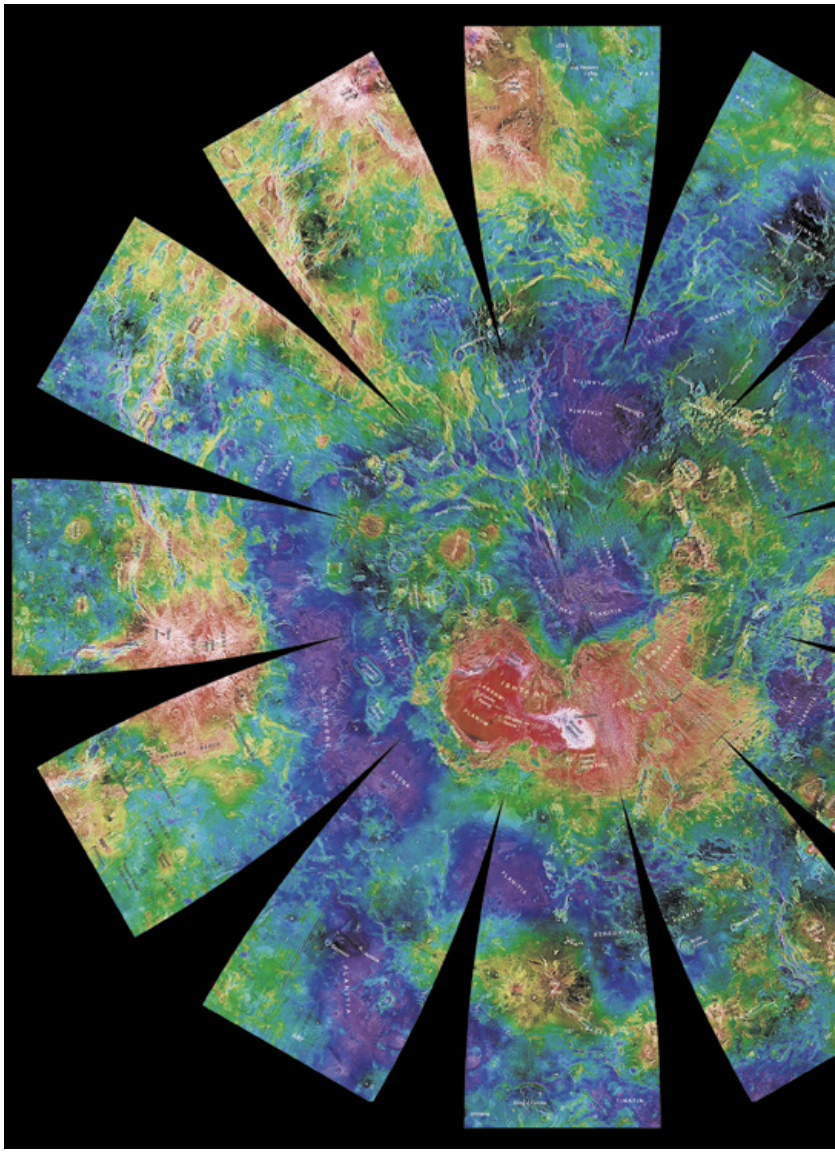
Without volcanism, there would be little surface water and no place for the origins of life. This cycling of volatiles helps to sustain Earth's atmosphere, which was crucial for the emergence of life. Similarly, continents, which provide a buoyant, stable platform above sea level for marine life to evolve onto land, are a product of plate tectonics. For these and many other reasons, understanding whether Venus has plate tectonics—and why or why not—is key.

On Earth, limited data suggest that plate tectonics began as early as four billion years ago, leaving little record. We do not really know how a planet transitions from a basalt-covered world, possibly with oceans, to an intricate system of moving plates with complex features. One leading hypothesis is that blobs of material from deep inside Earth called plumes burst onto the surface, initiating subduction—the act of one plate sliding under another. The hot plume weakens the lithosphere (which includes the crust and upper mantle) and pushes up, causing the surface to crack, or "rift." Pressure from the plume head can create violent volcanism, as observed on both Earth and Venus. The load on the cracked lithosphere can cause this layer to sink and prompt subduction, whereby one layer of the lithosphere slides under another. If this process happens often enough, the subducting plates link up, and plate tectonics begins.

This may be happening on present-day Venus. The lithosphere on Venus now is warm and thin—much like Earth's was back when plate tectonics started up. And some data show compelling similarities between features on Venus and terrestrial subduction zones. One example is Artemis Corona, a circular formation near the equator on Venus that is similar in scale and shape to the Aleutian trench that lies under the ocean along the coast of Alaska. Scientists have theorized that such Venusian features represent spots where plumes from the mantle are rising up to the surface and pushing the crust apart.

Furthermore, recent laboratory experiments and computer simulations suggest that these plumes are inducing subduction where they crack through the top layer of crust. In particular, the experiments explain why subduction seems to take place around only part of the circle: as the brittle lithosphere rips apart in the center, it splits into segments, just as paper rips into different wedges when poked with a pencil. As the lithosphere sinks, it continues to tear, forming segments. If these segments were to join, we would be seeing the initiation of plate tectonics on Venus.

Existing images of these features are too low in resolution for us to know for sure what we are seeing. But it appears that plate tectonics on Venus is in the early stages of development. The Magellan observations show no evidence of interconnected plates—rather we see isolated spots where subduction is beginning, in each case around one of these circular regions where plumes appear to be rising up. Two questions follow: Why did plate tectonics not develop sooner, and what course will it take now? As Venus cools more fully over time, the faults that are now opening may endure, allowing the planet to undergo the same transition to plate tectonics experienced on Earth. If we can watch the beginning of plate tectonics unfold on Venus, then this process and its accompanying atmospheric stabilization may be common on exoplanets on the path to habitability themselves.



GLOBAL MAPS of Venus from Magellan and Venera spacecraft data show diverse features, including the circular Artemis Corona (*box*), that could be indications of plate tectonics.

NASA/JPL/USGS

A BETTER VIEW

WE HAVE NEVER HAD BETTER REASONS to send a new major mission to the oft-ignored second planet from the sun. With high-resolution global imaging and spectra, we can answer compelling questions about volcanism and possible plate tectonics on Venus. Is the process truly occurring now? How do the surface activities relate to what is happening in the planet's interior? How do the conditions on Venus, such as its temperature, affect this tectonic activity? And are some surface features

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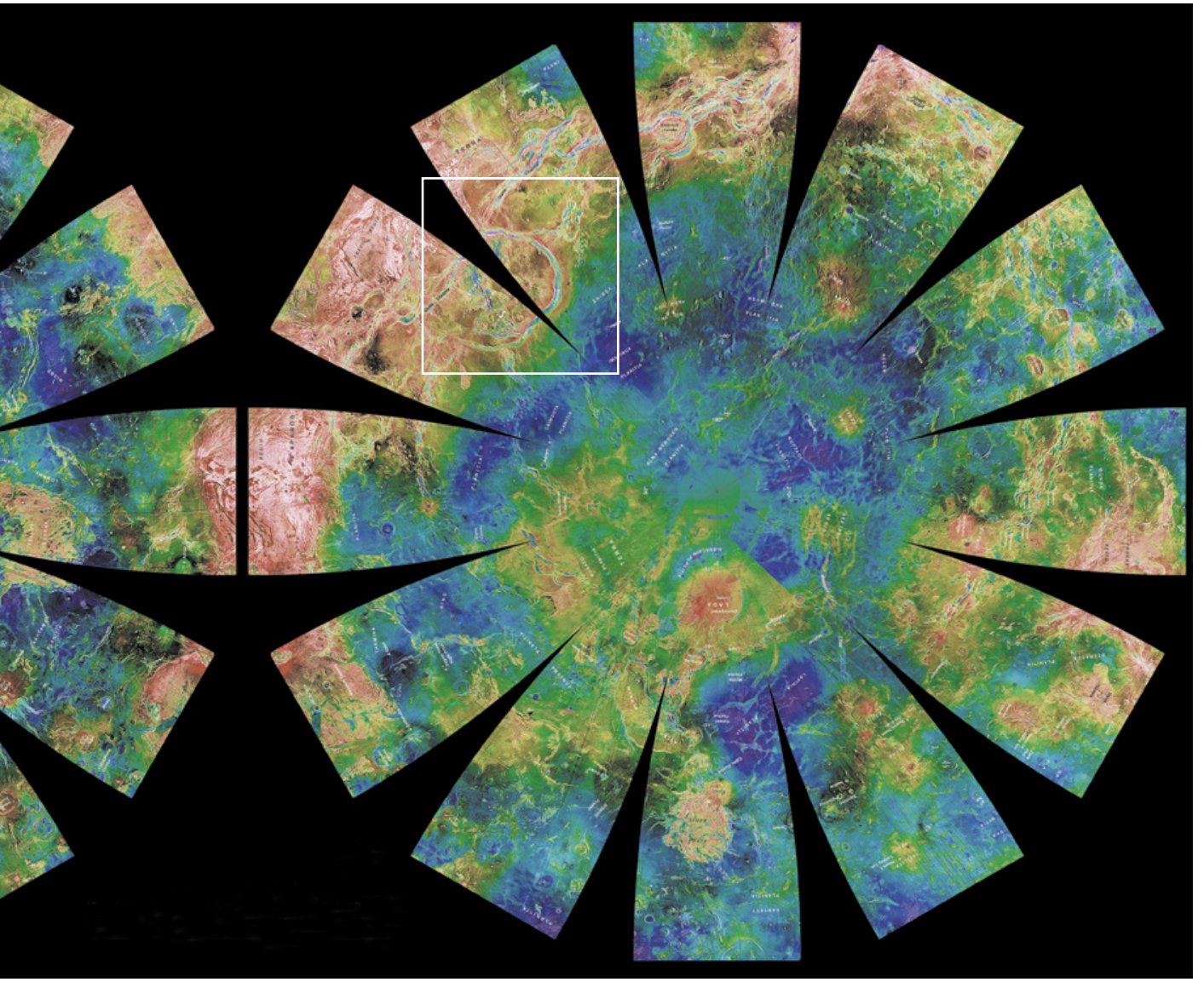

we see, such as the crinkles scientists call tesserae, remnants of a past, wet epoch?

In 2019 NASA solicited proposals for the next group of its smallest class of space probes, called Discovery missions. Another of us (Smrekar) and Dyar are leading one proposed mission called VERITAS (Venus Emissivity, Radio Science, InSAR, Topography, and Spectroscopy), which aims to map the surface in much greater detail than ever before. It will carry several instruments, including an imaging camera and spectrometer, to provide orders-of-magnitude-level improvements in topography resolution and the first-of-its-kind global composition map of the planet. Another Venus mission proposal is also in the works, with a tentative launch date around 2030.

More than 30 years after Magellan arrived at Venus, the generation of scientists who launched Magellan is growing older and retiring. A mission to Venus now will allow researchers to pass the torch to a new generation who can bring us closer to understanding why our planetary sister evolved so differently from Earth. Perhaps we may even discover what conditions are necessary for the emergence of life.

M. Darby Dyar is a mineral spectroscopist who studies extraterrestrial minerals and glasses from the moon, Mars, comets and asteroids. She is a senior scientist at the Planetary Science Institute and Kennedy-Schelkunoff Professor of Astronomy at Mount Holyoke College.

Suzanne E. Smrekar studies the different evolutionary paths for rocky planets, with occasional fieldwork at volcanoes. She is a senior research scientist and deputy principal investigator of the InSight and VERITAS Missions at the NASA Jet Propulsion Laboratory, where the mountain biking is awesome.

Stephen R. Kane is a planetary astrophysicist who has discovered hundreds of exoplanets and studies their potential for habitability. He is a professor in the department of earth and planetary sciences at the University of California, Riverside.

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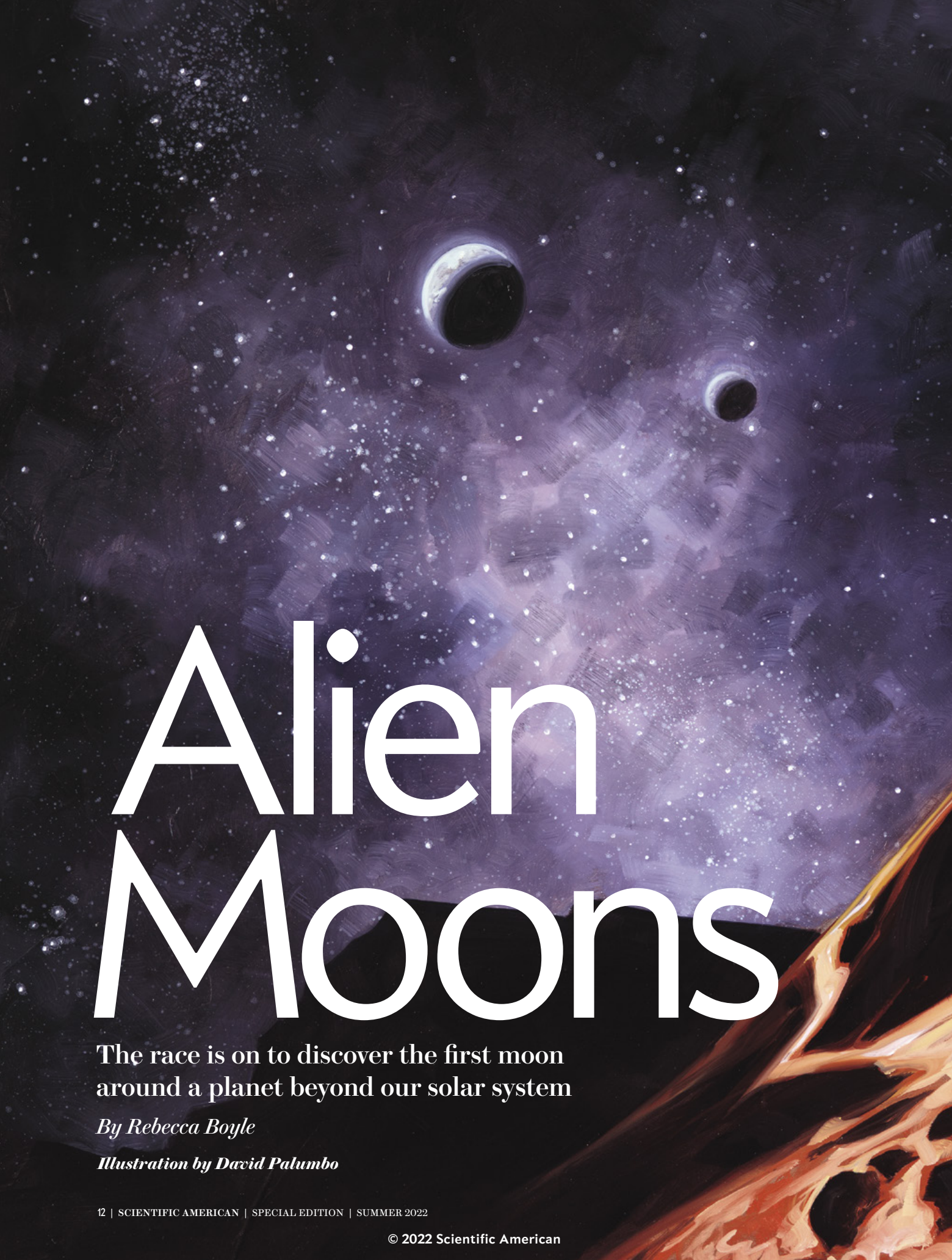

Alien Moons

The race is on to discover the first moon around a planet beyond our solar system

By Rebecca Boyle

Illustration by David Palumbo

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IN 2007 A NETWORK OF AUTOMATED TELESCOPES OBSERVED A STAR ABOUT 433 LIGHT-YEARS AWAY in the constellation Centaurus. The star dimmed noticeably for at least 54 days, with its feeblest light measured around April 29. In 2012 astronomers determined that this star hosted a huge, Saturn-size gaseous planet orbited by a spectacular array of 37 rings. Just as Saturn does, this world known as J1407b has a gap in its ring system. Scientists suggested the gap may indicate a moon with roughly the mass of Earth.

Until the end of the 20th century, the only known planets were the seven worlds with which Earth shares the sun. This situation changed with the earliest exoplanet discoveries in the late 1990s and was completely overturned starting in 2009, when the Kepler space telescope opened its lens. We now know that the cosmos is peppered with planets, that there are far more planets than stars, and that these worlds come in almost every imaginable size, location and type. Arguably for the first time since the days of Galileo Galilei, discoverer of Jupiter's largest moons, and astronomers such as Huygens himself, humans are seeing our place in the universe with fresh eyes. We have yet to find a distant planet that looks just like home or to confirm that an exoplanet is orbited by a moon of its own. But we are getting closer.

Astronomers began speculating about exomoons in the early 2000s, after several exoplanets began winking into distant starlight, and searches since 2018 have turned up a few promising candidates. Locating a moon outside our solar system would mark another reorientation of our cosmic perspective. We will learn whether moons are ubiquitous or rare; whether they are usually large or small, compared with their planets; whether they often form along with their planets or are created in later cataclysms; and whether they come in groups or typically fly solo. We will be able to understand whether our solar system is unique and whether Earth and its solitary, huge moon stand alone.

"Every time we see an exoplanet, I think it's a mirror on our own history," says Alex Teachey, a postdoctoral researcher at the Academia Sinica Institute of Astronomy and Astrophysics in Taiwan and co-discoverer of a possible exomoon of the exoplanet Kepler-1625b. "In what ways are we common and in what ways are we uncommon? Just as we started seeing with exotic exoplanet systems, we could be surprised in what we see with exomoons as well."

THE PERKS OF A MOON

EARTH REMAINS UNIQUE, in this solar system and everywhere else we have looked so far. It is the only planet known to harbor life. It is the only planet whose active innards sculpt its outer face, in the form of plate tectonics, a process that itself plays a role in the dispersal and evolution of life. It is the only planet with an atmosphere thick enough to support liquid water, a climate that has remained stable for millennia and a just-right distance from its sun that keeps it warm but not too hot. These conditions exist at least in part because of Earth's moon.

The moon's role in Earth's history goes back to the very beginning, some 4.5 billion years ago, when a planet the size of present-day Mars collided with the infant Earth. The cataclysm left behind an incandescent, oblong Earth and a boiling moon. The moon has been cooling and moving away from Earth ever since. The planet became more spherical as the moon began to recede, and Earth's crust flexed under the resulting tidal force. The early crust deformed, possibly causing the onset of tectonics. The moon's recession also slows Earth's spin, lengthening our day by almost two milliseconds every century.

The moon's heft is significant relative to Earth's; our planet's mass is only 81 times greater than that of our satellite, a ratio many times smaller than for the other moons of our solar system. Saturn, for instance, outweighs Titan 4,200-fold. The moon's pull guards Earth's axis, keeping the planet near a constant 23.5-degree tilt with respect to the sun. This configuration protects Earth's climate over millennia, as opposed to Mars, which lacks sizable moons and thus wobbles on its axis between zero and 60 degrees at the extremes every few million years—a change that drives dramatic climatic shifts. The moon provides the primary influence over Earth's tides, which shape coastlines and the life in the oceans. Our moon's tides most likely played a role in

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EARTH'S MOON, seen here from the International Space Station, has shaped the history of our planet and helped make it habitable for life.

NASA

evolution, shepherding the first plants and tetrapods from the salty marshes of the coasts and onto land.

The moon is more than a silent, spectral satellite; it is a world unto itself, which Earth's occupants have both used and contemplated since the first sighted beings looked skyward. Earth would not be Earth without the moon. Neither would the oceans, or poetry, or religion, or science, or any of us.

If Earth's singular past provides any prologue, exoplanets might be different without moons, too. Unmooned exoplanets might be lifeless rocks, doomed to tilt like Mars through the millennia, freezing or boiling and preventing atmospheres and life from holding on. Exomoons themselves, if they exist, might even be better places for life than their planets. The search for life beyond our solar system may need to focus on planets with the possibility of moons and even on the moons themselves.

Although Huygens could not have known it, his Titan, an orange ball of haze dotted with methane and ethane rivers and lakes, is quite planetlike. It would not be hospitable to us or any life we would recognize, but it contains liquid and an atmosphere, meaning it contains a chance for mixing of ingredients and a chance for life. Saturn, with its intense gravity and clouds of ammonia, would never be a safe haven for life; the same scenario exists for Jupiter, practically a half-star with absurd radiation belts and gas layers that would be fatal to us. But the same cannot be said of their moons.

"Because of our solar system, we know Jupiters can have significantly large moons that can have water," says Chris Fox, a graduate student at Western University in Ontario. "If you have a Jupiter in the habitable zone of its star, you could see a moon that is like Earth, and the moon may have life. Given the number of moons that there [likely] are, maybe life on moons is even more common than life on planets."

Exomoons, in other words, may be habitable themselves, and they might help make their host planets habitable, too. Finding them will bring us closer to understanding those worlds as well as our own.

AN INTRIGUING CANDIDATE

ASTRONOMERS SUSPECTED the cosmos was full of worlds and their moons long before the Kepler telescope saw its first light. In 1999 Paola Sartoretti and Jean Schneider, now both at the Paris Observatory, became the first to propose searching for exomoons using the transit method.

If a star and its planets are arrayed on a flat plane as viewed from Earth—as if you were looking at the solar system from the side rather than the top down—the star will appear to dim for a brief period because a planet has moved in front of it. This eclipselike fron-

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tal pass is called a transit. When transits repeat on a regular schedule, you can usually be confident an orbiting planet is causing the dimming. The Kepler telescope used this method to find planets for a decade. Sartoretti and Schneider argued that moons orbiting at wide distances from their host planets would be detectable in this way, too, if the moon were beside the planet at the time of the transit. A host star could dim more than usual or could even dim twice if the moon's orbit were sufficiently distant from the planet. If you were standing on the planet during the transit, for widely separated moons, the moon's phase would have to be near first or last quarter; a full moon or new moon, when the moon is directly opposed to the star, would not make a discernible dent in the planet's transit.

Even if exomoons orbited close to their host planets, making a secondary dimming implausible, astronomers might still detect moons by looking at how a planet's repeating transit pattern appears to change over time, Sartoretti and Schneider suggested. Often transits recur with metronomelike precision. But sometimes they are a little off, with a transit beginning or ending just a bit earlier or later than scientists predict—an effect called transit timing variation. This can happen because other planets orbit the star and tug on one another, but it can also happen when a planet is hosting a large moon.

To understand why, it helps to understand that Earth's moon does not orbit our planet exactly. Rather both bodies orbit their mutual center of mass, called a barycenter. The barycenter is still located on Earth because the planet is more massive than the moon. (To be precise, the barycenter is located *in* Earth, in the mantle, offset from Earth's gravitational center.) As a result, Earth wobbles very slightly as it orbits the sun. This wobble is one thing Sartoretti and Schneider recommended looking for.

In 2017 Teachey and David Kipping, an astronomer at Columbia University, sifted through data from the Kepler telescope to look for any indications of a moon interfering with the star's light. They analyzed some 300 planets, hoping to find a population of moons. They found just one candidate: Kepler-1625b.

They applied for time on the Hubble Space Telescope and were surprised when they got it, both recalled. Then they studied the Hubble data for a year, with part of that time spent learning how to use them. When Kipping and Teachey finished their analysis, their Hubble observations showed that the planet's transit began sooner than it should have, implying a moon was by its side. The planet's transit time varied by about 20 minutes in five years of data. "We know there's something pushing that planet around," Kipping says, "and we think it's a moon."

Teachey and Kipping posted their paper to a preprint server in early 2018, and it was ultimately published in October 2018 in *Science Advances*. They say the evidence supports the existence of a Neptune-sized moon around Kepler-1625b, which itself is many times the size of Jupiter. Kipping and Teachey stopped short of claiming a discovery. "I think people were frustrated by the way we reported it," Teachey says. "People thought we were both trying to get credit for a discovery but also kind of covering our rear because we're not fully claiming it. I understand people's frustration—is it there or not there? But there's a lot of unknown unknowns."

Immediately following their initial announcement, other astronomers jumped into the fray. René Heller, an astronomer at the Max Planck Institute for Solar System Research in Göttingen, Germany, replicated part of Teachey's findings but found insufficient evidence for a moon. Laura Kreidberg, who studies exoplanet atmospheres, was unable to confirm a key part of the results. Kreidberg, now director of the new Atmospheric Physics of Exoplanets Department at the Max Planck Institute for Astronomy in Heidelberg, Germany, recalled having a friendly but somewhat awkward conversation with Teachey a few months after his paper published. "Alex worked so hard on this, and I don't want to minimize what he did," she recounted. "I sort of swooped in there with a bunch of years of experience using this instrument. I'm rooting for Alex. Both of us want the moon to be there. I mean, how cool would that be?"

THE RACE

EXOMOON ATTENTION only grew in the months after Kipping and Teachey's announcement. Soon teams of researchers were poring over Kepler data on their own, trying to find transit variations that could indicate moons. Others turned to instruments such as the Very Large Telescope's Spectro-Polarimetric High-contrast Exoplanet REsearch tool (SPHERE). Cecilia Lazzoni, currently a postdoctoral fellow at the University of Exeter in England, claimed finding a giant exomoon using a SPHERE survey. In a paper published in *Astronomy & Astrophysics,* she described it as a companion to a very low-mass brown dwarf, a dim object between a planet and a star that does not fuse hydrogen but is many times the size of Jupiter. Lazzoni's world and its accompanying body may be more like binary giant planets than a world and a moon. If such objects are common, astronomers will have to grapple with how to define what constitutes a planet and a moon.

In 2019 Phil Sutton of the University of Lincoln in England reanalyzed the super-Saturn, J1407b. The planet and its rings were first discovered by Eric Mamajek, now at the NASA Jet Propulsion Laboratory, and several colleagues. Sutton wanted to find evidence for moons that orbit outside the ring, as most of Saturn's do, so he set out to determine whether J1407b's 37 rings are sculpted in the same way. He could not find any evidence for external moons guiding the gaps in the rings and instead found that an external moon would likely shred the disk apart. "We all get excited that we might have actually found something," Sutton

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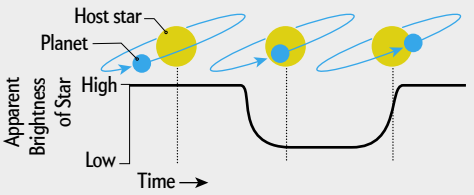
How to Detect an Exomoon

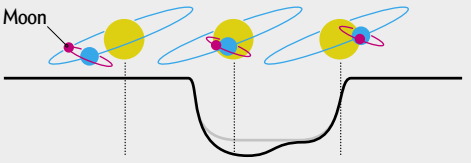
Astronomers are still getting a handle on discovering planets around other stars, but some scientists are already dreaming of detecting moons around those alien worlds. In the past few years several teams have claimed possible detections of exomoons, but none have been confirmed. There are two main ways researchers have looked for these distant satellites: by observing a star's dimming when the planet and moon both pass in front of it and by seeking signs that a moon has caused its planet to wobble.

The Transit Method

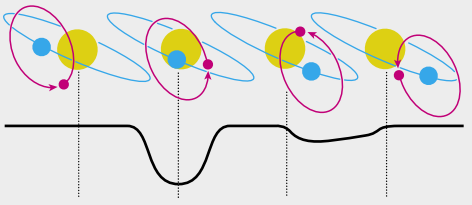
If a planet crosses between its host star and Earth, it will slightly dim the star's light that reaches our telescopes. This technique is responsible for most of the exoplanets known.



Moons could show up this way, too. If the planet and moon are oriented just so, a host star could dim more than usual during planet transits where the moon also blocks light.



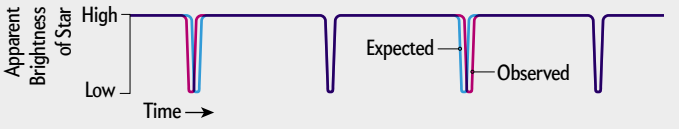
Or the host star could even dim twice if the moon's orbit was sufficiently distant from the planet.



Transit Timing Variations

Even if an exomoon is not positioned in a way that dims a star's light, astronomers might still detect it by looking at how a planet's transit pattern appears to change over time. Often transits recur with metronomelike precision.

But sometimes a transit occurs just a bit earlier or later than expected. This pattern could indicate moons circling planets, causing both to wobble a bit around their mutual center of mass. The wobbling will alter the timing of the planet's transits and change the precision of the repeating light pattern.



says, but reanalysis often dampens hopes. "It's just really tricky to confirm."

Then, in the summer of 2020, Fox, the Western University grad student, peered through more Kepler data. He and his adviser, Paul Wiegert, scrutinized 13 Kepler planets and found eight with transit timing variations that can be explained by exomoons. But, as Fox pointed out, the variations could be something else, too; the possibilities range from stellar activity such as flares to other planets. "In many cases, we were able to match the transit timing variation pattern with a moon, but in all the cases, we could explain them by the presence of a second planet," he says.

Teachey was critical of the work when Fox posted it to a preprint server that summer and equally critical of coverage that claimed Fox was describing moons when he really described moon-or-planet scenarios. In a young and rapidly growing field, especially one with high stakes for career-making discoveries, some growing pains are inevitable, Teachey says. "We're not trying to stifle people working on moons, and we don't want to come across like we're being gatekeepers," he says. "But at the same time, this is part of the game. We're going to call into question conclusions that in our view are not supported by the evidence." Fox's paper was published in 2021 in *Monthly Notices of the Royal Astronomical Society*.

In November 2020 Kipping hosted the first-ever exomoon meeting, an informal conference held over Zoom that brought together some 80 researchers from around the world. The scientists discussed new detection methods, theories for moon and exo-ring formation, new constraints on exomoon sizes and candidates, and related subjects. "I think we need to be a little more organized as a community to have a better shot," Kipping says.

A definitive detection remains elusive in part because the astronomers are all asking so much of their telescopes and their data. The wee blip in brightness that results from a planet transiting its star can be hard enough to see on its own. Comparing that with a shift in transit timing by just a few moments—remembering that the objects in question are hundreds of light-years away—is an excruciatingly exacting measurement.

Kreidberg says she is frustrated that she was unable to figure out why she and Teachey could not reach the same answer, using the same Hubble data. They shared each other's processing methods, and she tried to closely replicate his steps but could not reconcile the findings. "My only regret is that we weren't

Graphic by Jen Christiansen

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JUPITER'S MOON Europa harbors a buried ocean that might be hospitable to life.

NASA/JPL-Caltech/SETI Institute

able to figure out what the difference was," she says. "The takeaway for me was, we are really pushing the limits of what Hubble can do. It was designed to look at faint distant galaxies, not nearby planets with moons. We're doing the best we can with data processing, but it's a fine art to pull the signal out."

Other challenges are geometric. Because of Kepler's laws (that is, Johannes Kepler, who discovered the rules governing planetary motion and for whom the planet-hunting telescope is named) and Newton's laws, moons' orbits are more stable within a certain distance from their planets, known as the Hill radius. The closer a planet orbits to its star, the likelier that the star's gravity will interrupt the moon's orbit, potentially sending it spiraling into the planet or out of the star system entirely. But the data from Kepler, Hubble and other observatories usually capture planets that orbit near their stars—often very near, closer than even Mercury is to the sun. Although these planets are relatively easier to find than planets farther away, they may be more likely to be moonless. "If we're looking at planets that are transiting their stars, we are looking at planets whose gravitational influence has been severely diminished and are less likely to host a moon," says Stephen Kane, a planetary astrophysicist at the University of California, River-

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side. He published a paper in 2017 arguing that compact planetary systems, such as the TRAPPIST-1 system of seven terrestrial planets, are unlikely to host any moons at all.

Planets that wind up at greater distances from their stars, such as Jupiter and Saturn, are more likely to host moons, notes Alice Quillen, an astronomer at the University of Rochester, who has studied the super-Saturn J1407b. When a planet is more distant from the star, the star is less likely to fuss with the planet's gravity, allowing a moon to stay in place. If far-flung exoplanets resemble the solar system's own outer worlds in size and composition, they may also be likelier to grab planetary crumbs, errant asteroids and dwarf planets. Neptune's moon Triton is thought to be a captured dwarf planet from the distant Kuiper belt, a small world like Pluto, that was swept into Neptune's embrace after the solar system formed.

But large, distant planets are hard to find, partly because they take a long time to orbit their stars—one year on Jupiter, equaling one transit, takes almost 12 Earth years, meaning astronomers would have to watch such a planet for more than two decades before finding a definitive signal. And they are hard to spot because they can be confused with other objects. Periodic dims in a star's constant light are as likely to be caused by star pairs that occasionally move in front of each other as outer planets. "You can't find things in outer solar systems because it is too easy to confuse with eclipsing binaries," Quillen says. "You have to spend a lot of time trying to get rid of stuff that isn't what you want."

Stars themselves can also confuse the signals. The sun turns out to be a particularly quiescent star; other stars tend to be more active, churning out flares and radiation and developing spots that can also affect their apparent brightness. "The trouble with measuring the brightness of a star is that if you improve the precision too much further, you start to run into stellar activity," Kane says. "Stars will produce noise that is comparable or even greater than the signal expected from a moon. It essentially creates a ceiling you can't rise beyond, and that's a really big challenge."

Undaunted, some astronomers are turning to creative mathematical and observational methods. Apurva Oza, a lecturer at the University of Bern in Switzerland, is looking for an Io. The Jovian volcanic moon is visible with binoculars or a modest telescope; it is one of the four satellites Galileo Galilei observed in 1609. But viewed with sensitive instruments, Io is one of the most glaringly obvious objects in the sky. It positively emanates sodium and potassium, which it spews into space in vast quantities as Jupiter's gravity rends its innards and Io's volcanoes erupt. Io's exosphere can extend up to 500 times Jupiter's radius, Oza says. What is more, its signature would be visible no matter where the moon is located; an astronomer studying a transiting planet would not have to worry about the exomoon's phase. An exo-Io could be behind the planet, and its vast plasma cloud would still be detectable with the right instruments. "If you spray that gas everywhere, you just enshroud it, and you'll see it during transit," Oza says.

Spectrographs on several telescopes can already detect volatile gases within and around stars, he adds. Some have detected sodium, potassium and other signatures, which are often unexplained. "The missing factor could be a moon," Oza says. "It doesn't seem that outlandish when you think about it that way." He notes that an exo-Io would hardly be a place to look for any exobiology, however: "We're not looking for habitability here. We're looking for explosive environments, which is most of the universe."

THE WAY FORWARD

ASTRONOMERS HOPE the James Webb Space Telescope, which launched in December 2021, will be able to hunt for exomoons with greater precision. Kepler was designed to find Earth-sized planets around sunlike stars, so objects smaller than Earth can be difficult to pick out. Researchers frequently used the Spitzer Space Telescope, but it was retired in January 2020. Not much else on Earth or in the heavens can find exomoons at the moment, so astronomers are relying on better data-processing methods—and getting ready to wait.

"Part of our job remains not just looking for these things but coming up with better ways to look for them," Teachey says. "People think a discovery is a eureka moment. And it's more like, 'Let's see if it fails this test. And this test.' Then you're like, 'Well, it's kind of holding up.'"

Ground-based observatories such as the Extremely Large Telescope, under construction in Chile's Atacama Desert, could also spot exomoons under the right circumstances. The European space telescope PLAnetary Transits and Oscillations of stars (PLATO), set to launch in 2026, could help the search, too. Further into the future, satellites such as the Large UV/Optical/IR Surveyor (LUVOIR)—which might launch sometime in the mid-2030s—could provide excellent exomoon-hunting capabilities. But all these projects are still years away.

"With exomoons, it's kind of Hubble or bust right now," until James Webb gets going, Kipping says. In the meantime, he hopes the burgeoning exomoon community will continue figuring out new strategies for working with the data that exist so far. Kreidberg is also hopeful that James Webb will find exomoon signals but concedes that a definitive discovery may still be a while off.

"This is the cutting edge," Kreidberg says. "Figuring out what we know and how well we know it is an evolving process. You have to be an optimist to work on exoplanets." And, maybe, exomoons. SA

Rebecca Boyle is an award-winning freelance journalist in Colorado. Her forthcoming book *Walking with the Moon: Uncovering the Secrets It Holds to Our Past and Our Future* (Random House) will explore Earth's relationship with its satellite throughout history.

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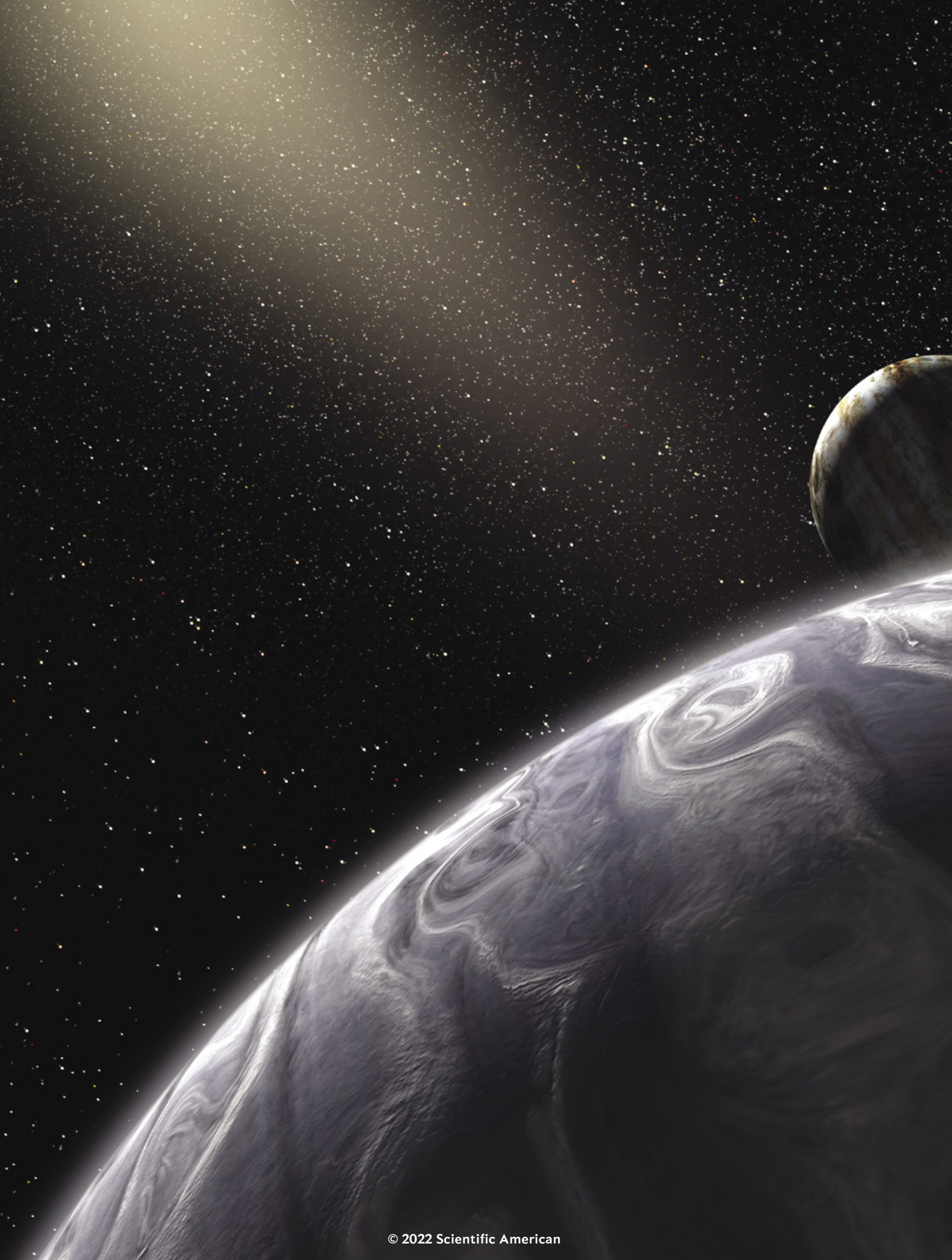

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On a Moon Far Far Away

Kepler-1708 b-i appears to be a giant moon orbiting a Jupiter-sized planet thousands of light-years from Earth

By Jonathan O'Callaghan

Illustration by Ron Miller

ARTIST'S IMPRESSION reveals an exomoon (*left*) orbiting a giant planet around a distant star.

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AND THEN THERE WERE TWO—MAYBE. ASTRONOMERS SAY THEY HAVE FOUND a second plausible candidate for a moon beyond our solar system, an exomoon, orbiting a world nearly 6,000 light-years from Earth. Called Kepler-1708 b-i, the moon appears to be a gas-dominated object, slightly smaller than Neptune, orbiting a Jupiter-sized planet around a sunlike star—an unusual but not wholly unprecedented planet-moon configuration. The findings appear in *Nature Astronomy*. Confirming or refuting the result may not be immediately possible, but given the expected abundance of moons in our galaxy and beyond, it could further herald the tentative beginnings of an exciting new era of extrasolar astronomy—one focused not on alien planets but on the natural satellites that orbit them and the possibilities of life therein.

There are more than 200 moons in our solar system, and they have an impressive array of variations. Saturn's moon Titan possesses a thick atmosphere and frigid hydrocarbon seas on its surface, possibly an analogue of early Earth. Icy moons such as Jupiter's Europa are frozen balls that hide subsurface oceans, and they may be prime habitats for life to arise. Others still, such as our own moon, are apparently barren wastelands but could have water ice in their shadowed craters and mazelike networks of tunnels running underground. An important shared trait among these worlds, however, is their mere existence: six of the eight major planets of our solar system have moons. Logic would suggest the same should be true elsewhere. "Moons are common," says Jessie Christiansen of the California Institute of Technology. "In our solar system, almost everything has a moon. I am very confident that moons are everywhere in the galaxy."

The only problem is finding them. We can look for exoplanets in a number of ways, such as spying the dip in light they produce as they move in front of their star, an occurrence known as a transit, or getting a telltale glimpse of their gravitational tug on their host star. Finding exomoons, which are by nature decidedly smaller than the planets they orbit, is much more difficult, however. "They're just so small," Christiansen says. To date, only one truly plausible candidate has been found: Kepler-1625 b-i, a supposed Neptune-sized world orbiting a Jupiter-sized exoplanet about 8,000 light-years from Earth that was reported in October 2018. But even the existence of this more behemothic world has been called into question by subsequent analysis.

Kepler-1708 b-i's existence was first hinted at in 2018 during an examination of archival data by David Kipping of Columbia University, one of the discoverers of Kepler-1625 b-i, and his colleagues. The team analyzed transit data from NASA's Kepler space telescope for 70 so-called cool giants—gas giants, such as Jupiter and Saturn, that orbit relatively far from their stars, with years consisting of more than 400 Earth days. The team looked for signs of transiting exomoons orbiting these worlds, seeking additional dips in light from any shadowy lunar companions. Then the researchers spent the next few years killing their darlings, vetting one potential exomoon candidate after another and finding each better explained by other phenomena—with a single exception: Kepler-1708 b-i. "It's a moon candidate we can't kill," Kipping says. "For four years we've tried to prove this thing was bogus. It passed every test we can imagine."

The magnitude of the relevant smaller, additional dip in light points to the existence of a moon about 2.6 times the size of Earth. The nature of the transit method means that only the radius of worlds can be directly gleaned, not their mass. But this one's size suggests a gas giant of some sort. "It's probably in the 'mini-Neptune' category," Kipping says, referring to a type of world that, despite not existing in our solar system, is present in abundance around other stars. The planet this putative mini-Neptune moon orbits, the Jupiter-sized Kepler-1708 b, completes an orbit of its star every 737 days at a distance 1.6 times that between Earth and the sun. Presuming the candidate is genuinely a moon, it would orbit the planet once every 4.6 Earth days, at a distance of more than 740,000 kilometers—nearly twice the distance of our own moon's orbit around Earth. The fact that only this single candidate emerged from the analysis of 70 cool giants could suggest that large gaseous moons are "not super common" in the cosmos, Christiansen says.

The apparently large size of this exomoon, compared with its host planet, is "surprising," Kipping

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says, but not wholly unexpected: Kepler-1625 b, the planet that the previous exomoon candidate Kepler-1625 b-i purportedly orbits, appears to have a similar, if slightly larger, configuration. If both these moons truly exist, that could be telling us something very interesting about possible planet-moon configurations in the galaxy, namely, that giant worlds could host equally giant moons. That in itself raises questions about the genesis of such worlds. It is unlikely that such a large moon could directly form in orbit around a planet, with the planet more likely to sweep up any potential satellite-birthing material, suggesting another origin story is more probable.

"One scenario is this moon got captured by the planet as the planetary system was forming," Christiansen says. "Early planetary systems are quite violent, chaotic places. We see examples of capture in our own solar system: for instance, Triton, one of Neptune's moons. We think that was captured. So we know that this can happen; we just hadn't scaled it up to the idea that a Jupiter-sized planet could capture a Neptune-sized moon."

Not everyone is sold on this moon's supposed existence, however. René Heller of the Max Planck Institute for Solar System Research in Göttingen, Germany, says he is not sure that the transit signal the team has seen is the result of a moon. "It doesn't convince me," he says. Instead, Heller adds, the dip in light could simply be the result of natural variations on the star, such as sunspots we see on our own sun, passing across its surface at the same time as the planetary transit. Kipping and his team, for their part, say they have ruled out such a possibility because the dip supposedly caused by the moon began before the planet started to pass in front of the star.

Laura Kreidberg of the Max Planck Institute for Astronomy in Heidelberg, Germany, says she "wouldn't call it a slam dunk yet," but the result is "absolutely worth following up" to try to see another transit from the purported moon. We will not be able to do so immediately, however. Given the long orbit of the planet, it and its possible moon will not transit again until 2023, Kipping says, meaning we would have to wait until then to try to spy the exomoon again. If the exomoon really is there, the James Webb Space Telescope (JWST), launched in December 2021, should be able to nearly instantly confirm or refute its existence. "It would be a piece of cake for Webb," Kipping says. "It could find moons smaller than Europa around Jupiter. It's a ridiculously powerful telescope."

That in itself raises an exciting possibility: JWST could be used to perform some sort of survey to look for exomoons. In the way its predecessor, the Hubble Space Telescope, has made huge strides in exoplanet science, JWST might prove to be defined by its contribution to exomoons. "My team right now is planning out what an exomoon survey strategically would look like for Webb," Kipping says. "It will be the first time in human history that will be possible. I'm really excited about the future."

The reasons for doing so are severalfold. Once we start finding exomoons in abundance, we will start to get a true handle on their variability and importance. Tides from our own moon, for example, may have played a role in Earth's habitability, leading to the evolution of life in tidal pools. The study of exomoons may tell us more about the planet-formation process, too. "If we want to have a comprehensive understanding of how planet formation works, we need to understand moons," Kreidberg says. And there is another, more simplistic reason to study them: "Moons are cool."

> "In our solar system, almost everything has a moon. I am very confident that moons are everywhere in the galaxy." —Jessie Christiansen
> *California Institute of Technology*

Exomoons themselves may also represent prime targets in the hunt for life. Given they can seemingly range in size from small to Earth-sized and beyond, it is reasonable to assume that some rocky exomoons may orbit gas giant planets within their stars' habitable zone, where liquid water can exist. "This is one of those cases where science fiction might precede science fact," Christiansen says. "You have the example of the movie *Avatar* of a habitable moon around a gas giant. In *Star Wars,* you have habitable moons around gas giants. You can technically create a rock around a gas giant that has the average radiation from the sun such that it could have liquid water on the surface."

There are complications, though. A moon around a giant planet would experience a considerable gravitational push and pull from that larger world, which, in extreme circumstances—such as those of Jupiter's moon Io—can result in intense volcanic activity. The radiation from gas giants such as Jupiter can be deadly, too. And such systems can have peculiar characteristics. "If you're lined up right, you'd have your day and night from your rotation but an additional day-night cycle from going behind the planet," Christiansen says. "There are almost certainly rocks of the right temperature around gas giants. Whether or not they're habitable is an open question and something a lot of people are excited about." SA

Jonathan O'Callaghan is a freelance journalist covering commercial spaceflight, space exploration and astrophysics.

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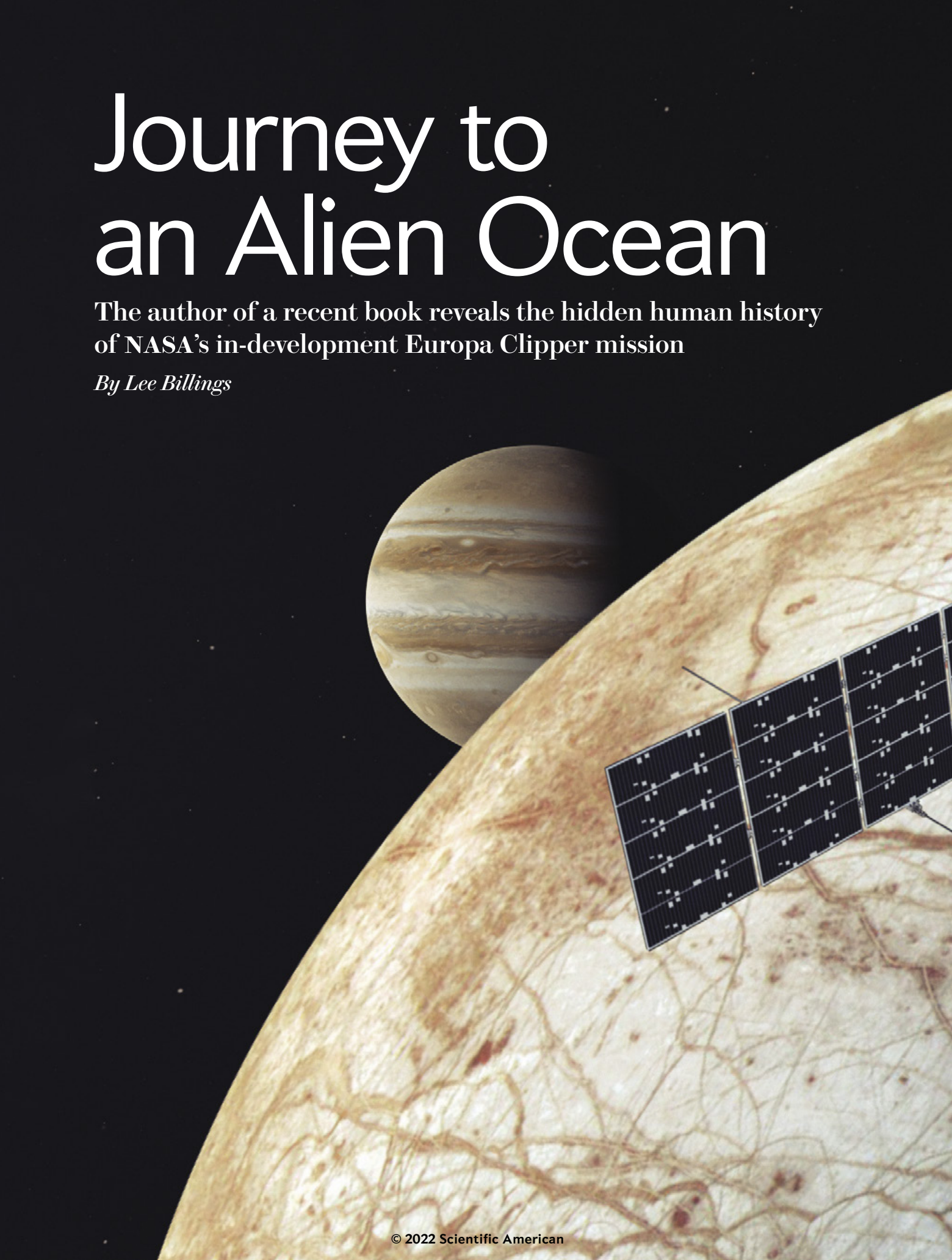
Journey to an Alien Ocean

The author of a recent book reveals the hidden human history of NASA's in-development Europa Clipper mission

By Lee Billings



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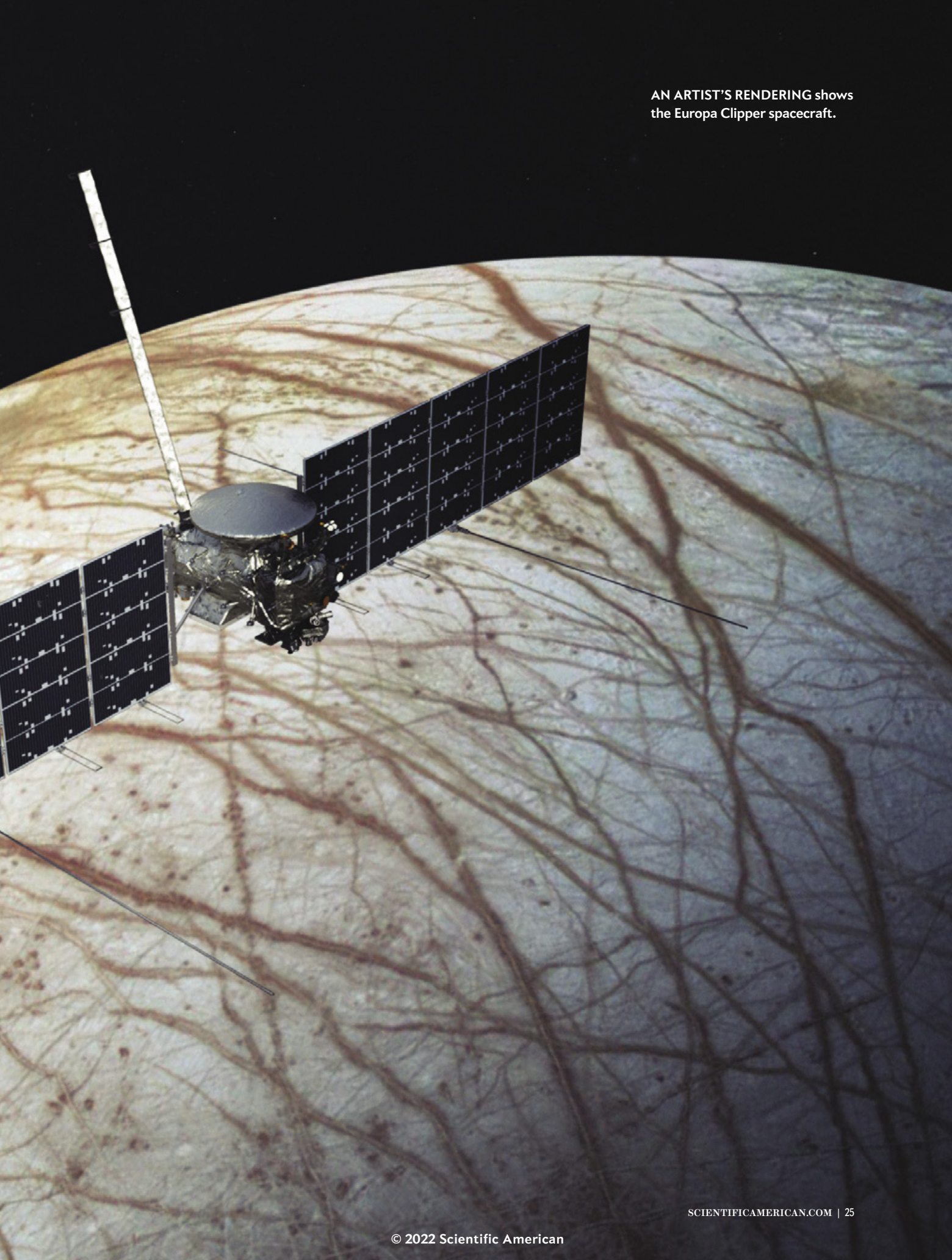

AN ARTIST'S RENDERING shows the Europa Clipper spacecraft.

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THE MOST EXCITING INTERPLANETARY MISSION FOR THE EARLY 21ST CENTURY is arguably not a robot named Perseverance currently roving around Mars gathering samples for a future return to Earth. Instead it is a NASA spacecraft that could launch later this decade to Europa, an enigmatic moon of Jupiter that boasts an enormous ocean—bigger than all of Earth's oceans combined—beneath an icy crust. Called Europa Clipper, the mission could lift off as soon as 2024 to study the moon's subsurface abyss with the goal of gauging its potential habitability and the distinct possibility of discovering a "second genesis" there. Many astrobiologists consider Mars to be a prime target for seeking out signs of ancient, now extinct extraterrestrial life because of its relatively Earth-like conditions billions of years ago. Europa, in contrast, has never really been like Earth at all, but it still may offer the solar system's best prospects for harboring alien organisms that are alive *right now*.

That makes the central narrative of David W. Brown's 2021 book *The Mission: A True Story* all the more intriguing. Despite the overwhelming scientific and popular appeal of sending a spacecraft to look for life within Jupiter's watery moon, the quest to make Europa Clipper a reality has been a decades-long uphill battle. The fact that the mission became NASA's next great planetary science project—and that it even exists at all—is a triumph over what, at times, seemed to be insurmountably long odds. Brown, a Louisiana-based journalist, spent several years following the key scientists, engineers, bureaucrats and politicians behind the mission. The result is a definitive account of Europa Clipper's inception—and of the often heroic and sometimes tragic human struggles behind each and every robotic emissary sent voyaging to worlds beyond.

SCIENTIFIC AMERICAN spoke with Brown about his book, Europa Clipper's long journey to the launchpad, the reason Mars is the "Death Star" of planetary science, and more.
[*An edited transcript of the interview follows.*]

First off, I want to commend you: I've followed this topic for years, but I still learned an enormous amount by reading your book. By focusing on the people and the politics behind Europa Clipper, you've revealed the many other dimensions outside of science that must come together to make interplanetary exploration happen. I think there's an enduring value to your work here, in a historical sense, that goes beyond just telling a good story.
I'm humbled. Thank you very much.

You're welcome! What I'm getting at is that one could say* The Mission *is not really about going to Europa at all because you've written and published it well before the spacecraft even reaches the launchpad. What would you say it's about?
Thematically, this book is about how different people handle crossroads in their lives. Each of the characters, early on in his or her career, has some moment, some decision point, where things could have gone either way.

Consider the case of Louise Prockter, for example, who is now chief scientist of the Space Exploration Sector at the Johns Hopkins University Applied Physics Laboratory and was a crucial early contributor to Europa Clipper. She didn't travel through the typical grade-school-to-college-degree pipeline that most people in the field did. She was an adult with a career when she decided to make a life change and pursue a university degree. And she would go on to become one of the most important researchers in all of planetary science. Bob Pappalardo, the project scientist of Europa Clipper, throughout his

NASA/JPL-Caltech (*preceding pages*)

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career, could have, at any time, put the Europa project aside—it would have been the smarter move, professionally. But something in his character wouldn't allow him to do that. He *had* to get a mission flying. At NASA headquarters, Curt Niebur's job as a program scientist in the planetary science division would have been so much easier if he had just marked a clean line across Europa in his portfolio and said, "Next," but he didn't. And this goes down the line for every character in the book.

It also applies more broadly to NASA and even the field of planetary science as a whole. Institutions and communities have had to make hard decisions in terms of exploration priorities and how to handle the perennial financial maladies that come from pursuing pure science. All of these things, and many more, ultimately came together to yield admission to Europa. Any single element that had gone the other way might have derailed the entire project.

DAVID W. BROWN

What inspired you to approach this subject in the first place?

The initial spark of a book emerged from a realization that after New Horizons flew by Pluto and after the planned conclusions of the Cassini mission at Saturn and the Juno mission at Jupiter, humankind would not have any active spacecraft exploring planets beyond the asteroid belt. The outer solar system would go dark for the first time since the 1970s.

Humanity was going to lose something important when that happened. And it bothered me a lot—as an American, as a human being who sees our possible future on other worlds and as someone interested in science. You know, other than war, it sometimes seems like space exploration is the only sort of human endeavor where the pronoun used is always "we": *We* go to war. *We* landed on the moon. And whenever that endeavor is diminished, I think it's a loss for all of us.

At the time, Europa exploration was not much more than a series of studies. But it was obvious to me and so many others that it was our best hope for rekindling exploration of the outer planets—to say nothing of its implications. I mean, as a storyteller, you're always on the lookout for high-stakes narratives. And certainly, if, in fact, life is one day found in the oceans of Europa—and conceivably complex life—I mean, that would have implications for science, philosophy, religion and of course geopolitical priorities. It would be a galvanizing moment in human history. And I hoped desperately that there was a story there.

The first person I spoke with was Louise Prockter, who told me she had 15 minutes to talk. And I said, "That's great. That's all I need." Three hours into the 15-minute conversation, I realized that after a decade of her working on one Europa study after another, this was probably the first time she had really opened up with any journalist about this amazing thing she was a part of and that had become a part of her.

And that seemed true for everyone who was part of the Europa mission. They fought in the trenches for so long to get this thing going. The more people I spoke with, the more I learned about the struggles and the setbacks, the heartaches and the loss, and the sheer adventure of it all. I fell in love with everybody in this book and with Europa. And, really, I fell in love with the whole field of planetary science.

I recall talking to you a little about this book a few years ago, and at the time, the tentative title was* One Inch from Earth. *Now, of course, it's* The Mission *(with a beautiful and elaborate subtitle). But as much as I love its current form, I'm a bit disappointed I never got to learn the meaning of the book's original title. What was that about?

I was attending an early test of the engines that are going to go into NASA's Space Launch System (SLS) rocket, which was originally intended to send this spacecraft to Europa. Todd May, who was, at the time, head of the SLS program, gave a brief talk about the process of bringing the rocket—or a mission—to the launchpad. And he said that flying a spacecraft three billion miles is easy. It's getting it one inch off the launchpad that's hard. And he'd meant that both on a technical level

Romney Caruso

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and also programmatically. It is very difficult to get these missions going, and I think most people don't realize that.

I remember when New Horizons flew by Pluto, I was telling a friend about how exciting it was, and she said, "Why did they even go to Pluto? It's not even a planet anymore!" And it impressed upon me the impoverished understanding that many people have about these sorts of missions. A lot of people seem to think a spacecraft is built in a matter of months, and then a rocket launches, and then the spacecraft just gets where it's going in a few weeks—almost as if NASA had just pulled a spacecraft off the shelf and fired it at Pluto. If all you noticed was the final approach and flyby, it would have seemed like a quick and easy thing, when, in fact, it took more than a decade to get that mission approved and nine years of flight time to reach Pluto. I mean, these are projects that can take entire careers and sometimes entire lifetimes.

There's obviously a direct connection to Europa, too. The phrase "one inch from Earth," to me, was evocative not only of the programmatic struggles of interplanetary exploration but also of the notion that complex life might exist just two planets over on this creepy little moon orbiting this weird, giant ball of hydrogen. If life can get started there, that probably means life in the universe isn't like a single cactus in the desert. It's more like a blade of grass in a meadow. It's going to be everywhere. And the idea of this cosmic discovery being so close to Earth really resonated with me, and it resonates within that phrase.

What most surprised you when you started writing this book?

What most surprised me was that I didn't know anything about the subject! I went into this thing, early on, feeling like I had a solid grip on the field of planetary science, how NASA works, how the scientific process works and the sorts of people who do this kind of work. But it struck me on almost the first day that I was clueless.

I remember the first time, several years ago, that I attended the annual Lunar and Planetary Science Conference near Houston, Tex. I went in ready to get all these amazing stories and learn all these spectacular things. But the science seemed as dense as a neutron star. I didn't know *anything*. I almost broke down in tears. It was bad! But it was liberating in a way because as soon as I realized how little I knew, I was able to approach the subject with a total beginner's mind and with a sense of wonder that I want the reader to experience, too. So I set a rule from the outset, which was that this book would have zero cynicism and irony. And I think I accomplished that goal.

If life can get started on Europa, that probably means life in the universe isn't like a single cactus in the desert. It's more like a blade of grass in a meadow. It's going to be everywhere.

You describe in the book the antagonistic relationship between Mars-focused folks and many others in planetary science, in which the Mars community's success in lining up missions comes at the expense of other targets for otherworldly exploration. It seems like the power of the Mars contingent is a force that has shaped NASA's entire planetary science division and really the whole field itself. Is that still the case?

I like to say that Mars is like the Death Star from *Star Wars*. Because at any given moment, it could destroy plans for any of the planets or moons under consideration for exploration. The Mars community has always been astoundingly good at that on a program level—maintaining a logical, carefully planned series of missions that all progressively lead to answering some high-impact science questions. But they are benefiting from another natural, built-in advantage: NASA is first and foremost a human spaceflight organization, and the agency wants to send astronauts to Mars. Astronauts are never going to land on Europa—not outside of science fiction, anyway. Astronauts are never going to land on Titan, and they're never going to land on Venus. But they're going to land on Mars someday. And because of that, there's an urgency to understand Mars in a way that doesn't exist for the outer planets.

All things being equal, though, if given the choice, I think NASA as an organization would still prefer to go to Mars—that was certainly true during the darkest days of the efforts to send something to Europa.

What were the darkest days, exactly?

Probably when Mars Sample Return got the highest recommendation for a flagship mission in the last Planetary Science Decadal Survey [a planning effort that provides recommendations to NASA and other government agencies for major science priorities every 10 years]. It's difficult to overstate how much of a blow that was to the heroes of the book. If not for the intervention of Congress—and particularly John Culberson, who was a Republican representative from Texas—Europa Clipper probably wouldn't have happened at all. Culberson wanted NASA to go to Europa because he thought finding life there could be a unifying force for the agency—increasing the chances it would regain the sort of funding and spirit it had during the Apollo era. And Culberson made it happen.

So, with NASA's Mars fever in mind, are things getting more equitable in planetary exploration in terms of destinations and priorities?

Maybe. The Mars community apparently wants small missions going forward—to study the Martian subsurface and any deposits of water ice, and so on. That creates an opening for other bodies in the solar system to have their moment.

My suspicion is that a sample-cache-

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return craft is going to fly to Mars regardless of the latest Decadal endorsements. That might be heretical to say aloud, but I think that we're just too close to achieving this thing that scientists have been seeking since the 1980s. We're not going to let those sample tubes sit on Mars for another 20 years. Because NASA and Congress seem amenable to getting an outer-planets flagship flying, I think we'll start seeing dual flagships fly every decade. But I might be entirely wrong about this, and the next 20 years could be the new Dark Ages for interplanetary exploration.

When I first started writing this book, the realm of the outer planets was one of nothing but woe and sorrow. But now I get a sense of optimism that wasn't there before. A lot of it is because Europa Clipper was eventually approved and because things such as Dragonfly, a plutonium-powered quadcopter planned to launch to Titan in the late 2020s, not only are going to explore another body but are going to do so with panache. When you have these sorts of audacious strides to places that are just incredibly compelling, I think it has kind of a halo effect for the broader community.

I hope you're right. Let's talk a bit about where the book ends—or rather the current status of the mission itself because, as you know very well, Europa Clipper has yet to get even one inch from Earth. The SLS rocket that was originally planned to launch it is not flying yet. And Culberson, the Europa program's champion on Capitol Hill, lost his reelection bid and is no longer in Congress.

I knew, while writing this book, that I would be chasing a moving target. I mean, for example, I would still be writing the book if I had to keep updating the status of the SLS, which, for most of the project's history, was its notional ride to space. So I chose to end the story in 2015, when Europa Clipper officially became the flagship planetary science mission of the American space program. You don't need the clichéd final scene with a rocket launch because that's nothing next to the epic struggle to make the mission real.

The Mission is in many ways a heist story. A group of smart people, each with different talents and connections, came together to achieve a common goal. It's like *Ocean's Eleven,* but instead of robbing a casino in the end, they get a spaceship called Europa Clipper.

In terms of where Europa Clipper is [as of early 2021], they have completed their critical design review and are beginning to build their spacecraft in force. You'll soon be able to go to the NASA Jet Propulsion Laboratory (JPL) at the California Institute of Technology and see this thing going from PowerPoint to reality—under construction in High Bay 1, a clean room where spacecraft are built.

Already smaller elements are in development. For example, you can see the wiring harness—the actual wiring that's going to fly to Jupiter—in a clean room at the Applied Physics Laboratory at Johns Hopkins. The mission's scientific instruments are well into development. There are actual parts and pieces that you can see now for a spaceship that is actually going to fly to what may be the most likely place in the solar system, aside from Earth, to harbor life. And it's thrilling to see how meticulous the process is—how many little things go into creating this giant thing.

When Europa Clipper is finished, the spacecraft is going to have the wingspan of a basketball court. But right now it's at a human scale, you know, of people twisting wires and bending metal. And that, to me, is deeply moving. They're doing some hard engineering right now, too. And as they do this hard engineering, the science is moving on. We're learning more about how plumes of water might be venting out of Europa's subsurface seas, where they're coming from, how the overlying ice behaves.

NASA's Juno spacecraft, currently at Jupiter, had its mission extended to do flybys of some of the planet's icy satellites. So we're going to be getting more data that hopefully help to shape the mission.

So is Europa Clipper out of the woods yet?

I think it would take a major crisis at NASA to actually shut the mission down, so it's probably going to fly one way or another. So from that point of view, yes, it's out of the woods. Now, in terms of the hard technical decisions that still need to be made and the financial elements that need to come together in the years ahead to keep the project on track, I'm less sanguine. Will Europa Clipper have enough money to fly, for example, the wide-angle camera? I don't know. I hope it will, but it has already lost instruments along its long path to the launchpad. So it's almost certainly going to fly. But what it looks like when it flies is still a little hazy.

In terms of the broader Europa exploration sequence, my Magic 8 Ball is much less optimistic. When John Culberson lost his election, Europa Lander, the follow-on mission in development, lost its greatest political champion and appropriator of funding. Europa Lander is important because Europa Clipper is probably not going to find life. It is studying Europa's habitability and will help determine where life most likely might exist on the ocean world. It will take a lander to set down on the surface and dig or drill or melt into it, looking for evidence of things that once wiggled.

It's an extraordinary mission and precisely the sort of "dare mighty things" project for which JPL is famous. More than $100 million has been spent on it, but work has now essentially stopped. If the lander gets an endorsement by the Decadal Survey, I have a feeling that work would resume immediately and that it would launch only a couple of years behind schedule. But that endorsement is a big "if."

What are you working on now? Might it be another book?

Yeah, a book about an adventurous team of scientists who have been doing pioneering work in Antarctica studying rapid sea-level rise. I've already been on one expedition down there with them. It's not a sequel, of course, but there is a lovely connection to *The Mission* because some of the world's foremost experts on Earth's cryosphere are also interested in Europa. Some people study Antarctica so they can understand Europa. It's certainly easier to get to, anyway!

Lee Billings is a senior editor for space and physics at *Scientific American.*

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Promising New Potential World

A candidate planet around Alpha Centauri could be a "warm Neptune" or a mirage. Either way it signals the dawn of a revolution in astronomy

By Lee Billings

FOR THE FIRST TIME EVER ASTRONOMERS MAY HAVE glimpsed light from a world in a life-friendly orbit around another star.

The planet candidate remains unverified and formally unnamed, little more than a small clump of pixels on a computer screen, a potential signal surfacing from a sea of background noise. If proved genuine, the find would in most respects not be particularly remarkable: a "warm Neptune" estimated to be five to seven times larger than Earth, the kind of world that galactic census takers such as NASA's Kepler and Transiting Exoplanet Survey Satellite missions have revealed to be common throughout the Milky Way. But even though it would be shrouded in gas and essentially bereft of any surface to stand on, its distance from its star would place it in the so-called habitable zone where liquid water could exist. No other planet has been directly seen in this starlight-drenched region around any other star because of the associated glare. And this world's celestial coordinates would be straight out of astronomers' wildest dreams—it would orbit a near twin of the sun called Alpha Centauri A, which also happens to be a member of a triple-star system that, at just shy of 4.5 light-years away, is the closest one to our own.

ALPHA CENTAURI, our nearest neighboring star system, rises above a unit of the European Southern Observatory's Very Large Telescope at the Paranal Observatory in Chile.

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Because of its proximity, the system's other members—a slightly smaller sunlike star called Alpha Centauri B and the diminutive red dwarf star Proxima Centauri—are also high-priority targets for astronomers, who have already indirectly detected the presence of at least two worlds around Proxima (including one that is likely rocky and within that star's habitable zone). Whether looking for real estate across town or around another star, location really is everything. The Centauri system is so close that it offers a unique front-row seat for scientists seeking to study the atmospheres and surfaces of any worlds that exist there, especially to seek out possible signs of life.

And astronomers long ago learned that planets are, in some respects, like household pests: where one is seen, others are likely to be found. Which is why, as tentative as they may be, the burgeoning crop of Centauri worlds hints at untold discoveries that are yet to be made and could profoundly transform views of our place in the universe.

Planets are, in some respects, like household pests: where one is seen, others are likely to be found.

The findings were reported in February 2021 in the journal *Nature Communications*. They come from an international consortium of planet hunters called Breakthrough Watch, via the inaugural science run of a one-of-a-kind "direct imaging" instrument called NEAR (New Earths in the AlphaCen Region), which operates on the European Southern Observatory's (ESO) Very Large Telescope (VLT) in Chile. The effort is named for its chief funding organization, Breakthrough Initiatives—the brainchild of the Silicon Valley billionaire Yuri Milner, who also sponsors related projects to search the heavens for signs of alien civilizations and to send pint-sized interstellar probes to the Alpha Centauri system.

"Alpha Centauri presents us with a magical opportunity because there is no better place in the sky to try to directly image small, potentially habitable planets," says study co-author Pete Klupar, Breakthrough Initiatives' chief engineer. "This was in some sense low-hanging fruit—for just $3 million, we were with our international partners able to build an instrument to take advantage of ESO's billions of dollars invested in its telescopes. But it's also like going after a needle in a haystack, which is why no one has ever done this before. Governments tend to build survey instruments, to look at large numbers of stars and guarantee a return on investment, whereas NEAR was purpose-built to just do this one, risky thing."

"When we collaborate on a global scale, we discover new worlds, and we keep advancing," Milner says. "The identification of a candidate habitable-zone planet in our celestial backyard will continue to power our curiosity."

THE BLIP

THE CANDIDATE'S tantalizing signal emerged from 100 hours of observations on the VLT, stretched across a total of 10 nights in the spring of 2019. By June of that year, as the Breakthrough Watch team members sifted through their observations, they began to realize they might have found something. Kevin Wagner, the study's lead author and a postdoctoral Sagan Fellow at the University of Arizona, first saw the telltale evidence of a planetlike blip cresting far above NEAR's instrumental noise. It happened while he was remotely processing a batch of data during a family vacation at Lake Jocassee, S.C. Measuring its brightness and sandwiching it between limits on planet masses and sizes calculated in previous studies by other groups, the Breakthrough Watch team estimated that—if the blip were indeed a planet—it would most likely be somewhere between Neptune and Saturn in size. By November he and his colleagues were certain the find was worth publishing, even if it proved not to be a world at all. (It would not be the first time our neighboring star system has fooled astronomers. Peer-reviewed claims of a small planet around Alpha Centauri B in 2012 evaporated a few years later, found to be products of stellar noise.)

"In a way, I hope we haven't detected anything this time, too," Wagner says. "Because what I'm most excited to find is an Earth-like planet in the habitable zone. The presence of a Neptune in the habitable zone of Alpha Centauri A would not rule out something smaller nearby, but it would limit some of the area in which we could hope for rocky worlds to exist there in the first place."

There is no shortage of other possible explanations for the weak signal, which is essentially a thermal wisp of infrared photons—that is, of heat—that seems to originate from a source at the outer edge of Alpha Centauri A's habitable zone. In visible light, a sunlike star outshines a small, rocky planet by a factor of billions. But in infrared, the star is dimmer and the planet is at its brightest, so this contrast ratio is "only" measured in millions.

For decades the difficulty of achieving even this more modest measurement limited direct imaging to hot giant planets orbiting far from their stars. That is, until NEAR was built. It is a mid-infrared coronagraph, a specialized instrument designed to blot out the bulk of a star's thermal glow at a tight wavelength of 10 microns. Augmented by adaptive optics to compensate for the blurring turbulence of Earth's atmosphere, in operation it switches its focus between Alpha Centauri A and B every tenth

VW Pics/Universal Images Group via Getty Images (*preceding pages*)

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of a second, using observations of each star to help calibrate those of the other. It progressively winnows out starlight, and it stacks frame after frame to allow any faint planetary light to accumulate and eventually be seen. But rather than betraying the presence of a planet, any resulting blip could instead be a far-distant background object, a clump of starlight-warmed dust, an asteroid belt circling around a star, or even the errant play of stray photons leaking from beamlines and spraying across sensitive optics inside the instrument. Wagner and his co-authors have already ruled out the first possibility (no known background star or galaxy can account for the blip), but the others remain in play to various degrees.

Confirmation of the blip's planetary status should have been relatively straightforward: simply attempt to observe it again after sufficient time has passed; if it is in fact a planet, its orbital motion will have swept it to a new and very different position around its star. Subsequent, more time-intensive studies with NEAR could then crudely measure the blip's colors to help eliminate the "dust cloud" hypothesis. But this was not to be—not yet, anyway—as the ensuing COVID pandemic shut down astronomical observatories and most everything else around the globe.

"The timing is such a shame," says Debra Fischer, a veteran planet hunter at Yale University. She is unaffiliated with the study, but her work with her former student Lily Zhao has placed the best-yet constraints on the planets that may or may not exist in the Alpha Centauri system. "If it's in the habitable zone around Alpha Centauri A, that's an Earth-like orbit, so observing six months later would probably have nailed it," Fischer says. "Without that, this isn't a planet-detection paper, it's a demonstration of NEAR's capability to monitor Alpha Centauri in the mid-infrared. But if this turns out to be right—oh, my God, it's huge."

BRAVE NEW WORLDS

FOR NOW, NEAR is the only coronagraph on Earth with a realistic chance of imaging Alpha Centauri's hidden worlds. But other instruments and facilities are already waiting in the wings to apply their own scrutiny to the system. Fischer's high-precision EXPRES radial velocity spectrograph and an even more advanced European counterpart, ESPRESSO, are both already operational. They could help indirectly confirm the planet candidate and others—and could estimate their masses—by watching for periodic wobbles each world's orbital tugging induces on its host star. A related technique, astrometry, could do much the same thing, pinpointing planetary masses by measuring how each world's gravitational influence slightly shifts its star's position in the plane of the sky. Such observations using the Atacama Large Millimeter Array in Chile or even a modest, Breakthrough-funded dedicated space mission could occur later this decade.

NASA's James Webb Space Telescope, which launched in December 2021, could also be capable of directly imaging the candidate planet if given one full day of observing time, according to a study led by one of Webb's foremost scientists, Charles Beichman of the California Institute of Technology. "Because Alpha Centauri A is a twin of our own sun and less than five light-years away, it really is our closest solar neighbor," Beichman says. "That makes it first among equals, of all the stars in the sky. No other system will lend itself to more detailed possible studies over the next several decades."

The space agency's follow-up mission to Webb, the Nancy Grace Roman Space Telescope, will also carry a coronagraph as a technology demonstration that could potentially snap pictures of the candidate.

And around the same time Roman may launch, a new generation of sophisticated coronagraphs mated to gargantuan ground-based observatories should begin operations that could in mere minutes produce images of Centauri planets that would currently require hours on hours of NEAR's time on the VLT. Armed with starlight-gathering mirrors 30 meters or more across, ESO's European Extremely Large Telescope and its American counterpart, the Giant Magellan Telescope, could both in theory gather enough light from a habitable-zone Neptune around Alpha Centauri A to let researchers study its atmosphere, sniffing out what familiar or alien chemistry occurs there. (A third behemoth, the U.S.'s Thirty Meter Telescope, is planned for a site in the Northern Hemisphere from which Alpha Centauri would not be visible.)

Finally, NASA and other space agencies are now studying concepts for a multibillion-dollar space telescope for the 2040s that could image and search for signs of life on small rocky planets around Alpha Centauri, as well as many other nearby stars.

All of which means that, even if this latest candidate from Alpha Centauri proves spurious, it still signals something quite real: a looming sea change in which planet-hunting astronomers shift from safe, statistical surveys to the more daring in-depth study of individual worlds, some of which might harbor life.

"Whether this thing is real is, to me, almost secondary," says study co-author Olivier Guyon, an innovator in direct imaging and chair of Breakthrough Watch. "Because either way it shows we're clearly opening a new era in the history of astronomy where, finally, after more than 20 years of hard work, we can at last perform direct imaging of another star's habitable zone. This is the 'game on' moment for the field." SA

Lee Billings is a senior editor for space and physics at *Scientific American.*

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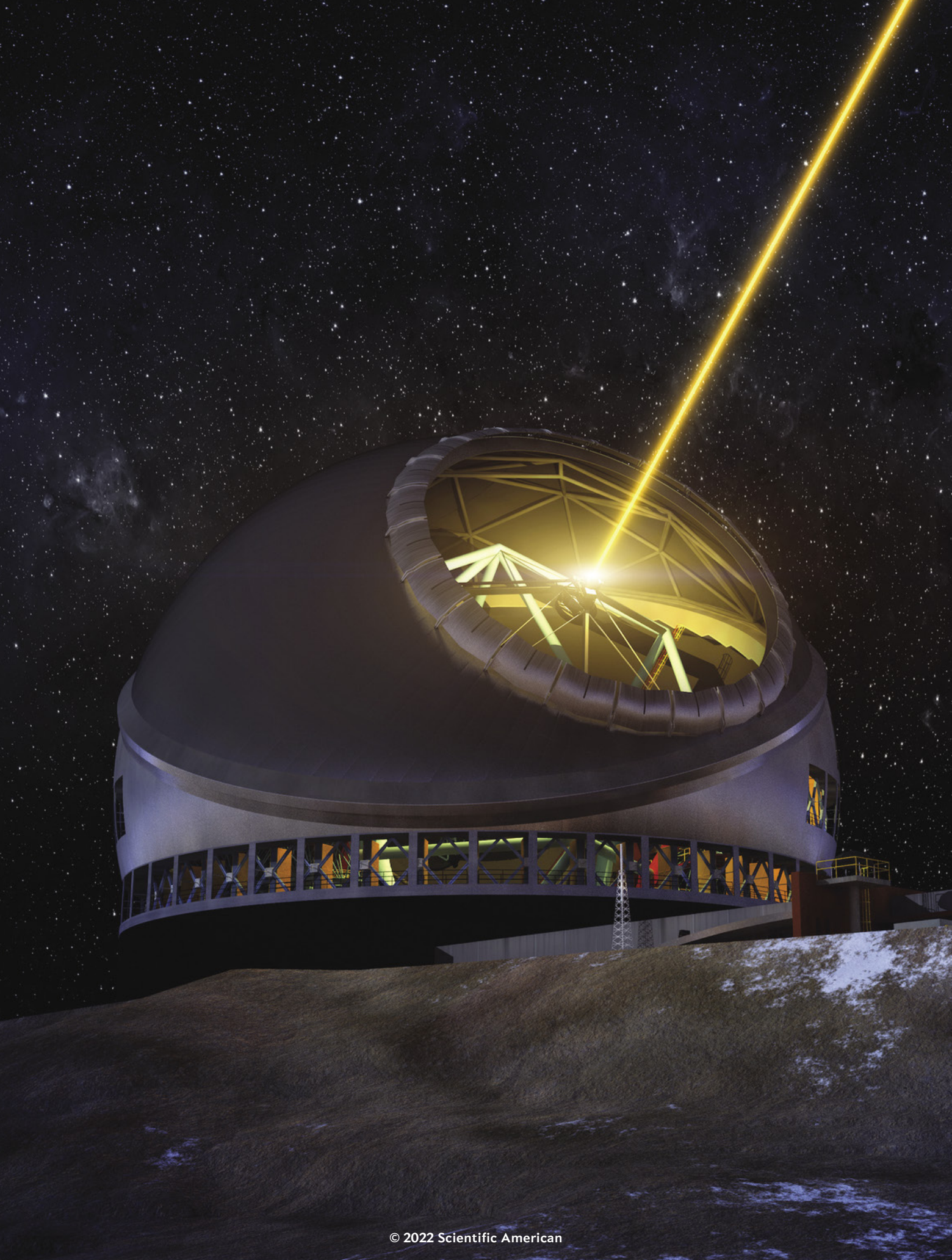

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Astronomy's Wish List

A major report outlining the highest priorities and recommendations for U.S. astronomy has finally been released, and hunting for alien life tops the list

By Lee Billings

ABOUT 20 YEARS FROM NOW astronomers will be in the midst of a revolutionary era of discovery, using new telescopes on the ground and in space to study the cradle-to-grave evolution of galaxies, probe the deepest origins of black holes, glimpse the earliest moments of cosmic time and gather breakthrough images of Earth-like worlds orbiting other stars. On average, those future researchers should also be healthier and happier, more diverse and inclusive, than their present-day counterparts.

AN ILLUSTRATION shows the Thirty Meter Telescope, an enormous (and hugely controversial) observatory astronomers hope to build on the summit of Mauna Kea in Hawaii.

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At least, that is the plan, according to the long-awaited major report "Pathways to Discovery in Astronomy and Astrophysics for the 2020s." Also known as Astro2020, it is the seventh iteration of a once-every-10-years "Decadal Survey" process for astronomy conducted by the National Academies of Sciences, Engineering, and Medicine. Its overarching purpose is twofold: to codify communal consensus on the future of the field via a ranked list of research priorities and, perhaps more important, to muster vigorous support from federal policy makers for sustaining the broader enterprise of U.S. astronomy.

In pursuit of those goals, this latest Decadal Survey deviates sharply from its predecessors, which traditionally reserved their highest recommendations for specific new telescopes that were tightly bound to a small slice of the electromagnetic spectrum. Instead Astro2020's highest space-based recommendation envisions a fundamental shift in the way that NASA plans and develops large, multibillion-dollar "flagship" astronomy projects. Dubbed the Great Observatories Mission and Technology Maturation Program, the initiative would invest $1.2 billion in the 2020s toward key enabling technologies for multiple proposed facilities in hopes of lowering the overall cost and risk associated with building and launching an entire fleet of next-generation telescopes to work together across a wide range of wavelengths, from infrared to x-rays.

> "In changing how we plan for the most ambitious strategic space projects, we can develop a broad portfolio of missions to pursue visionary goals, such as searching for life on planets orbiting stars in our galactic neighborhood—and at the same time exploit the richness of 21st-century astrophysics through a panchromatic fleet."
>
> —Fiona Harrison
> *California Institute of Technology*

The need for better management of NASA's future astrophysical mega projects is particularly urgent, given missteps in handling those of the present and recent past. The James Webb Space Telescope—the top flagship recommendation of the first Decadal Survey of the new millennium—finally launched in late 2021 after a series of near-catastrophic multibillion-dollar budget overruns and agonizing schedule slips. The top recommendation from the Decadal Survey of 2010, the Nancy Grace Roman Space Telescope, fared somewhat better but has still suffered costly setbacks that delayed its launch until circa 2027.

The premier result of Astro2020's top-recommended new program would be a supersize and far more sophisticated successor to the Hubble Space Telescope, which itself was the first in NASA's sequence of four "Great Observatories" sent aloft between 1990 and 2003. Like Hubble, it would operate in optical, infrared and ultraviolet wavelengths, but it would be perhaps three times larger than that storied observatory and built for an estimated $11 billion. Beginning development at the end of this decade for a notional launch in the mid-2040s, it would snap pictures of dozens of potentially habitable exoplanets and study their atmospheres for signs of life while also being a workhorse for a wealth of transformative astrophysics. Although it has no catchy formal name as of yet, astronomers are already referring to this project as "LuvEx," referencing two progenitor telescope concepts—LUVOIR (Large Ultraviolet Optical Infrared Surveyor) and HabEx (Habitable Exoplanet Observatory)—that fed into its creation. In short order, it would be followed by two additional facilities, one focused on the far infrared and the other on x-rays, each built for a projected cost of $3 billion to $5 billion. These follow-on facilities also reflect two preexisting proposals: the far-infrared Origins telescope and the Lynx X-ray Observatory.

A BRIGHT FUTURE

"THIS REPORT SETS an ambitious, inspirational, and aspirational vision for the coming decade of astronomy and astrophysics," said Fiona Harrison, a California Institute of Technology astronomer and co-chair of the Astro2020 steering committee, in a statement. "In changing how we plan for the most ambitious strategic space projects, we can develop a broad portfolio of missions to pursue visionary goals, such as searching for life on planets orbiting stars in our galactic neighborhood—and at the same time exploit the richness of 21st-century astrophysics through a panchromatic fleet."

Many astronomers are understandably ecstatic. "I believe this is the smartest, most executable and pragmatic Decadal Survey ever written," says John O'Meara, a vocal champion of the LUVOIR concept and chief scientist of the W. M. Keck Observatory on Mauna Kea in Hawaii. "The steering committee understood that we must redefine how we develop large missions so that we can realize this vision of new Great Observatories. They have brilliantly laid out how to achieve civilization-changing science in an uncertain world, and I hope NASA and other federal agencies embrace the spirit of the document."

"We stand at the threshold of a new golden era of discovery," says Heidi Hammel, vice president for science at the Association of Universities for Research in Astronomy. "Might we actually find evidence for life on another planet? This report, true to its name, lays out robust pathways to answer this question, and we can be the generation that answers it!"

Marc Postman, a distinguished astronomer at the Space Telescope Science Institute and a long-time proponent of large exoplanet-imaging observatories, holds a somewhat longer but no less gleeful view. "I'm walking on air right now because this is the culmination of a personal 15-year journey to get to this point. People ask me why I've spent time on this, because when [LuvEx] launches, I will certainly be retired but hopefully still in my mortal shell. I tell them I'm doing this for the future even if I never use it or see it get off the ground. And based on this Astro2020 report, the future is very bright. This is a generational initiative

TMT International Observatory (*preceding pages*)

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that is beyond any individual. Humanity is about to truly embark on a quest to learn whether we are alone in the universe."

Besides the big-ticket item of a life-hunting telescope as the first of a line of flagship Great Observatories, Astro2020's space-based recommendations also call for new once-per-decade "probe-class" missions with $1.5-billion cost caps, as well as significant spending to enhance astronomers' abilities to study split-second celestial phenomena in real time using not only light but subatomic particles and gravitational waves as well.

Astro2020's purview also extends to U.S. ground-based projects, which are typically funded and managed by the National Science Foundation (NSF) or occasionally by the Department of Energy. In this category, the report gives top ranking to a program to invest some $1.6 billion of NSF funding in the Giant Magellan Telescope (GMT) and the Thirty Meter Telescope (TMT), two gargantuan observatories in early phases of construction with an estimated total price tag in excess of $5 billion. With the GMT in the Southern Hemisphere, on a Chilean mountaintop, and the TMT in the Northern Hemisphere—either on the summit of Hawaii's Mauna Kea or on a peak on La Palma in Spain's Canary Islands—U.S. astronomers would gain profound new views of the entire sky through these extremely powerful telescopic eyes.

Other than helping these twin titans across the finish line, the report also recommends that the NSF and DOE jointly spend $660 million to create the Cosmic Microwave Background Stage 4 Observatory (CMB-S4), a facility to survey the big bang's afterglow in exquisite detail. An additional $2.5 billion of NSF funds would go to building the Next-Generation Very Large Array (ngVLA), a radio observatory that would be 10 times more sensitive than the aging facilities it would replace. Additionally, Astro2020 strongly endorses further upgrades to two projects opening entirely novel windows on the cosmos: the Laser Interferometer Gravitational-wave Observatory (LIGO) and the IceCube Neutrino Observatory, a facility with thousands of detectors arranged within a cubic kilometer of Antarctic ice. Paired with traditional observatories, LIGO and IceCube can help astronomers divine the arcane mechanics at play within the cores of exploding suns and between merging black holes and neutron stars.

POWER TO THE PEOPLE

THE PATHWAY FORWARD may be clear, but abundant obstacles remain. Much depends on whether Congress and the White House fully embrace—and fund—Astro2020's recommendations, a not at all certain prospect in the modern era of hyperpolarized politics. Then there is the looming issue of satellite mega constellations. Despite their benefits for global broadband connectivity, these groups of satellites pose existential threats to multiple major projects via the optical and radio contamination they inescapably add to exquisitely delicate observations of the heavens. For that increasingly dire problem, Astro2020 offers only the rather dissatisfying solution of engaging in interagency, as well as international, collaboration to devise better, more protective regulatory frameworks.

But as the authors of the report themselves note, despite such challenges, the success of their audacious vision may ultimately hinge on how they handle the most valuable assets of U.S. astronomy, which are not dollars but people.

"Our report says serious attention also needs to be paid to investments in the foundations of this research—including in the people who carry it out," said Astro2020 steering committee co-chair Robert Kennicutt, an astronomer who holds professorships at the University of Arizona and Texas A&M University, in a statement.

That recognition, deep in the Decadal Survey's bones, is one reason Astro2020 is "a huge win for U.S. astronomy," says Scott Gaudi, an astronomer at the Ohio State University and co-chair of the HabEx mission concept study. "The decadal steering committee really thought about how to create a balanced portfolio—not just with a new set of Great Observatories and projects like the GMT and TMT but also with significant support for basic things like more research grants and mid-scale programs. And that's exactly what we need to make the more ambitious parts of this vision even plausible in the first place."

In recent years the community has been left reeling not only from budget-blowing projects but also from sexual harassment scandals, anemic support for early-career researchers and their smaller-scale projects, and brutal asymmetries in work-life balance that have led to burnout and poor well-being. There is also a worrisome lack of diversity among the ranks. In this melting pot nation, the typical practitioners of astrophysics remain overwhelmingly white and male, with all the privileges, obvious or subtle, this entails—something keenly felt when, for instance, some of them seek to build new facilities on the sacred grounds of historically disenfranchised minority groups, as is the case of the TMT and the project's preferred construction site on Mauna Kea.

To remedy these and other social ills, Astro2020 recommends more spending on research grants and independent postdoctoral fellowships, increased funding and institutional support for diversity-boosting initiatives at the university and federal agency levels, and a formal recognition at NASA, the NSF and the DOE that harassment and discrimination are corrosive forms of scientific misconduct. With the TMT imbroglio at Mauna Kea clearly in mind, the report also calls for a "Community Astronomy" model of engagement that would seek to "respect, empower, and benefit local communities while advancing scientific research," according to a National Academies press release.

Such acts, says University of New Hampshire cosmologist Chanda Prescod-Weinstein, would be "steps in the right direction" to address the growing storm of cultural crisis cresting over the field's horizons. But even so—especially in the case of engaging with historically marginalized Indigenous people—she says this Decadal Survey's recommendations do not go far enough.

"Sometimes scientists have to accept a hard 'no' from Indigenous people," Prescod-Weinstein says. "Instead [Astro2020] focuses more on what the characteristics and quality of a collaboration between Indigenous communities and scientists should be. It never directly acknowledges the scenario that Indigenous people may not want to collaborate.... My view may change once I've had more time to sit with the report, but my first impression is that scientific goals are still supreme and that we are still not ready, as a community, to talk to non-astronomer Indigenous people as if they are our equals and their concerns matter as much as ours."

Lee Billings is a senior editor for space and physics at *Scientific American.*

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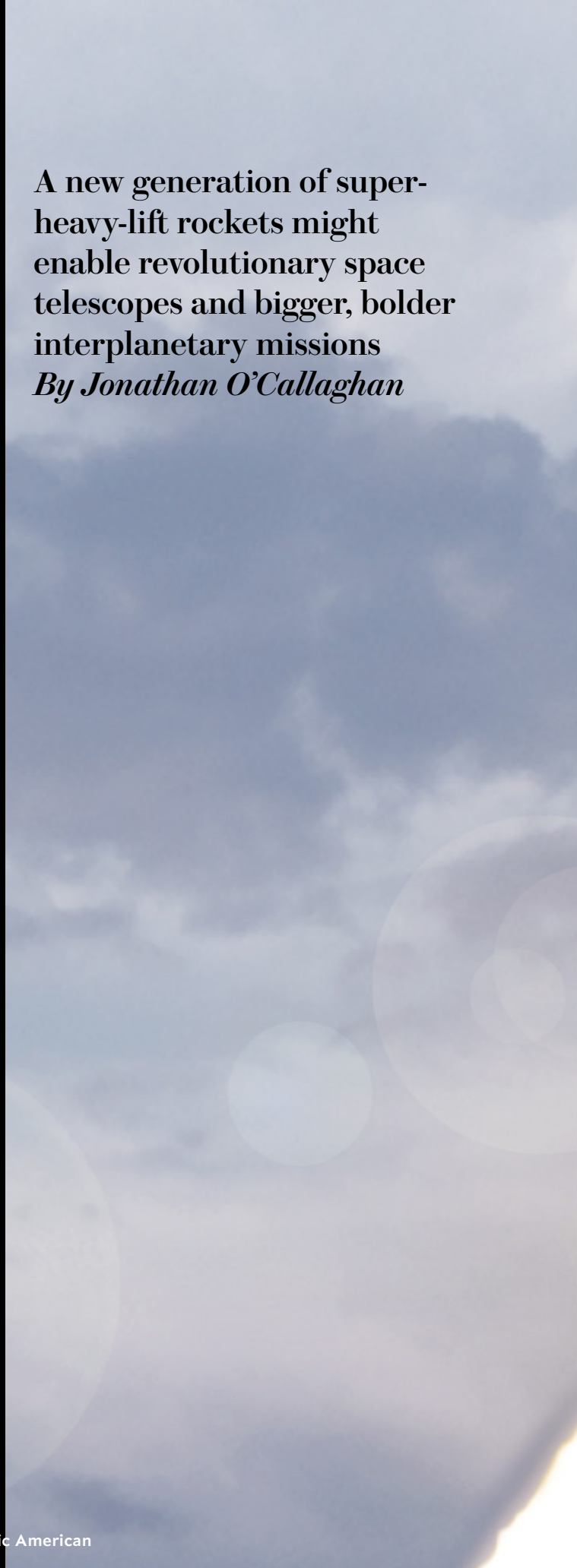
Super-Rocket Supercharge

A new generation of super-heavy-lift rockets might enable revolutionary space telescopes and bigger, bolder interplanetary missions

By Jonathan O'Callaghan



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NASA'S SPACE LAUNCH SYSTEM (SLS) moon mega rocket is topped by the Orion spacecraft.

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ASTRONOMERS BREATHED A collective sigh of relief as the James Webb Space Telescope (JWST) sprung to life. Getting the $10-billion telescope up and running following its launch on Christmas Day 2021 had been a nerve-racking affair. JWST would not fit into any modern rocket without being folded, and it had to rely on hundreds of moving parts to unfurl to full size once in space. Ultimately those efforts were successful, and the telescope has started returning some of its first calibration images to thrilled audiences back on Earth. Yet the experience left many astronomers wondering if there was a simpler way to build and launch telescopes of this size. "We were worried about the unfolding," says John Blevins of the NASA Marshall Space Flight Center. But with a larger rocket, "you don't have to unfold in space. You can do it on the ground."

As chance would have it, two such rockets are currently sitting on launchpads. Each should ultimately exceed the power of the mighty Saturn V, which sent the Apollo astronauts to the moon. The first, NASA's Space Launch System (SLS), is ready and waiting at Kennedy Space Center in Florida for its inaugural uncrewed voyage around the moon as part of the Artemis I mission—the opening shot in NASA's plan to return humans to the lunar surface in the 2020s. The rocket, tentatively scheduled for a launch in late August, is meant to be as reliable as possible and is therefore based, in large part, on legacy hardware from NASA's Space Shuttle program.

But a reliance on tried-and-true technology could be its Achilles' heel: some estimates currently peg the SLS's cost at an eye-watering $4.1 billion per launch. Presuming it is not scuttled by congressional appropriators feeling buyer's remorse, its massive size could eventually be a boon for scientists seeking to send larger, more ambitious spacecraft and telescopes throughout the solar system—and even beyond.

Over in Texas, Starship, a similarly capable but wildly different rocket being developed by SpaceX, is also in preparation to launch on its first orbital test flight, pending regulatory approval from the Federal Aviation Administration. The cost of the SLS seems so egregious because each multibillion-dollar rocket will be discarded after a single use, its components relegated to the seafloor as junk or left adrift in space. Such was the standard for most of the space age, but times have changed. Starship and its giant Super Heavy booster are instead built for endurance, landing back on the ground for rapid reuse similar to SpaceX's current fleet of Falcon rockets, which has already dramatically lowered the cost of reaching space. As big and bold as the SLS may be, experts say it pales in comparison with what Starship could achieve. "Starship holds the promise of transforming the solar system in a way we can't really appreciate," says Alan Stern of the Southwest Research Institute in Texas, who helms NASA's New

NASA (*preceding pages and above*)

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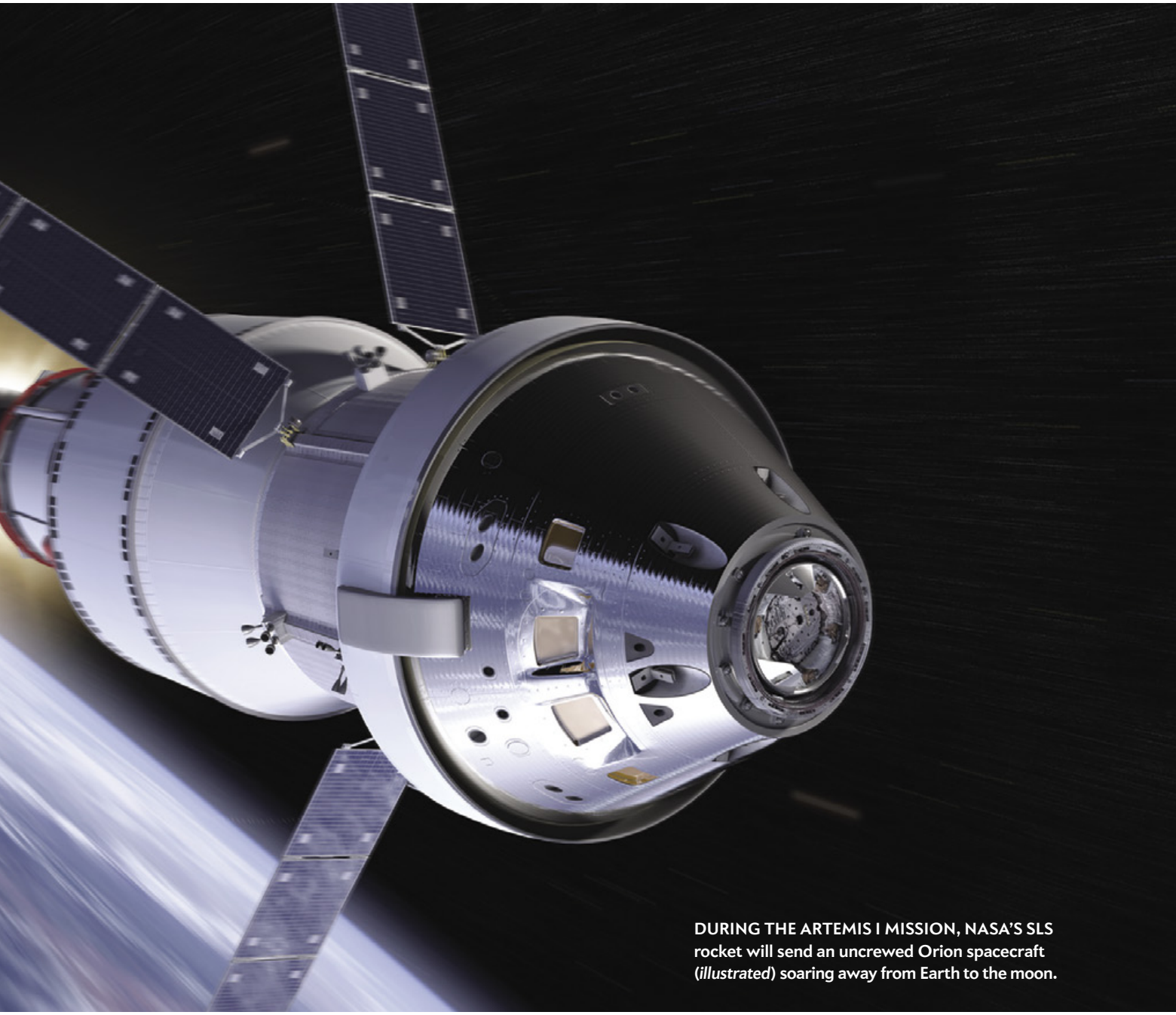

DURING THE ARTEMIS I MISSION, NASA'S SLS rocket will send an uncrewed Orion spacecraft (*illustrated*) soaring away from Earth to the moon.

Horizons mission, which flew by the dwarf planet Pluto in 2015. "It completely changes the game."

Either rocket's shroudlike payload fairing is spacious enough to fit cargo as big as or even bigger than JWST, all without the need to fold components into the world's most expensive origami. And both launchers will possess such immense thrust they can reach remote corners of the solar system on shorter time scales with larger spacecraft than smaller rockets. Starship alone, however, is designed to be refueled in space, meaning it could transport mind-bogglingly huge payloads to hard-to-reach locales such as Jupiter and Saturn—or anywhere else around the sun, for that matter.

As this hopeful new era of the super-rocket dawns, eager scientists are vying to be along for the ride. "These rockets can enable whole new classes of missions—to all the giant planets and the Kuiper belt objects, to the ocean world satellites and the dwarf planets of the solar system," Stern says. "They're across-the-board useful." Now many are busy drawing up ideas for what might be possible, at the moment focusing more on the SLS because of its greater maturity but keeping a beady eye on Starship and its potentially revolutionary capabilities.

THE SCIENCE LAUNCH SYSTEM?

AFTER ITS INITIAL MOONSHOT, NASA officials say, the SLS will primarily be used to launch the agency's Orion spacecraft with

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crew onboard. Those launches will work in tandem with NASA-contracted Starship launches, which will serve to land an Artemis crew on the moon as early as 2025—and perhaps one day send astronauts to the surface of Mars. "We expect approximately one human landing per year over a decade or so," NASA's administrator Bill Nelson said in a press conference on March 23. As a result, no SLS rocket is likely to be available to solely launch any sort of telescope or scientific probe into the solar system until the 2030s. "Given the demands of the Artemis program between now and the late 2020s, it's going to be very difficult to squeeze a science mission in that time frame," said Robert Stough, payload utilization manager of SLS at the NASA Marshall Space Flight Center, in a 2021 briefing.

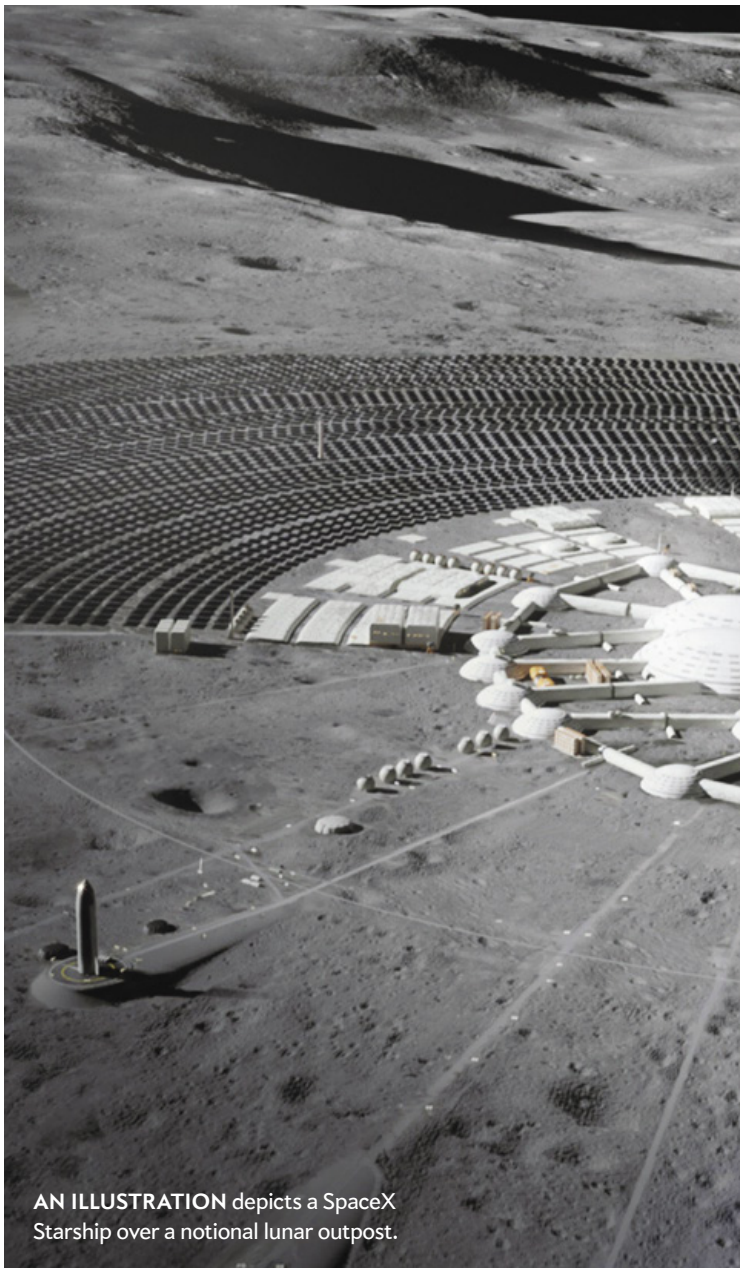
Consequently, in 2021 NASA switched the planned 2024 launch of its Jupiter-bound flagship mission, Europa Clipper, from the SLS to a SpaceX Falcon Heavy. Even so, agency officials are bullish that the SLS's exorbitant costs and sluggish launch rate can be improved, creating more opportunities for science missions. In his briefing, Stough estimated that $800 million or lower was an achievable target by the 2030s. According to a paper presented at a November 2020 American Institute of Aeronautics and Astronautics (AIAA) meeting, SLS's final, most powerful planned configuration could be supercharged with the addition of a new "kick stage" that would add propulsion to the top of the rocket. Such an upgrade would allow the SLS to send some 16 metric tons to Jupiter, about six metric tons to Neptune and one metric ton to interstellar space. The New Horizons mission to Pluto, by comparison, had a mass of half a metric ton. "There's no rocket right now that can carry anywhere near this payload," says Blevins, who is chief engineer of the SLS at Marshall.

On April 19, 2022, the National Academies of Sciences, Engineering, and Medicine released its much awaited Planetary Science and Astrobiology Decadal Survey, which recommends NASA's otherworldly science priorities well into the 2030s. As part of the survey, NASA solicited studies from scientists on mission concepts that the agency might consider for targets in the outer solar system. Three of those suggested using the SLS to allow faster, bulkier missions: a Pluto orbiter, an orbiter and lander to Saturn's moon Enceladus, and an orbiter and atmospheric probe to Neptune. "We wanted to use existing or very near-term technology," says Kirby Runyon of the Johns Hopkins University Applied Physics Laboratory (JHUAPL), who is part of the proposed Neptune mission. "The SLS is the furthest along in its design and maturation of any of the very large vehicles."

Runyon's group's proposal, Neptune Odyssey, would launch as soon as 2031 on an SLS rocket to enter orbit around Neptune in the 2040s. The mission would provide unprecedented insight into a planet that has been visited only once, in a fleeting flyby from the Voyager 2 spacecraft in 1989 on its journey out of the solar system. Odyssey would study Neptune and its largest moon Triton for four years while also deploying a probe into the planet's stormy atmosphere. Slightly smaller rockets such as the Falcon Heavy could also get Odyssey to Neptune but only via various add-ons that would raise the mission's cost and complexity while reducing its tolerance for error. That approach "is definitely more risky," Runyon says.

The Enceladus Orbilander, meanwhile, would be a mission to seek out signs of life within the Saturnian moon's ocean, which is ejecting plumes of water vapor and organic molecules through cracks in its overlying icy crust. The spacecraft could fly through and sample the plumes before landing on the moon's surface to perform in situ studies. The SLS, again, makes a mission like this easier than it would be with a smaller rocket, which would require gravitational boosts from planetary flybys in the inner solar system. "This means we don't have to design the spacecraft to survive both the warm conditions of the inner solar system and the frigid conditions out at Saturn," says Shannon MacKenzie, the concept's lead at JHUAPL.

Even the SLS has its limitations, though. Assuming a launch in 2031, the giant rocket would still take nearly three decades to propel a proposed orbiter, called Persephone, to Pluto. And despite its immense size, the SLS is still limited by its inability for on-orbit refueling to boost its carrying capacity once in space. In their more audacious dreams of cosmic exploration, scientists have



AN ILLUSTRATION depicts a SpaceX Starship over a notional lunar outpost.

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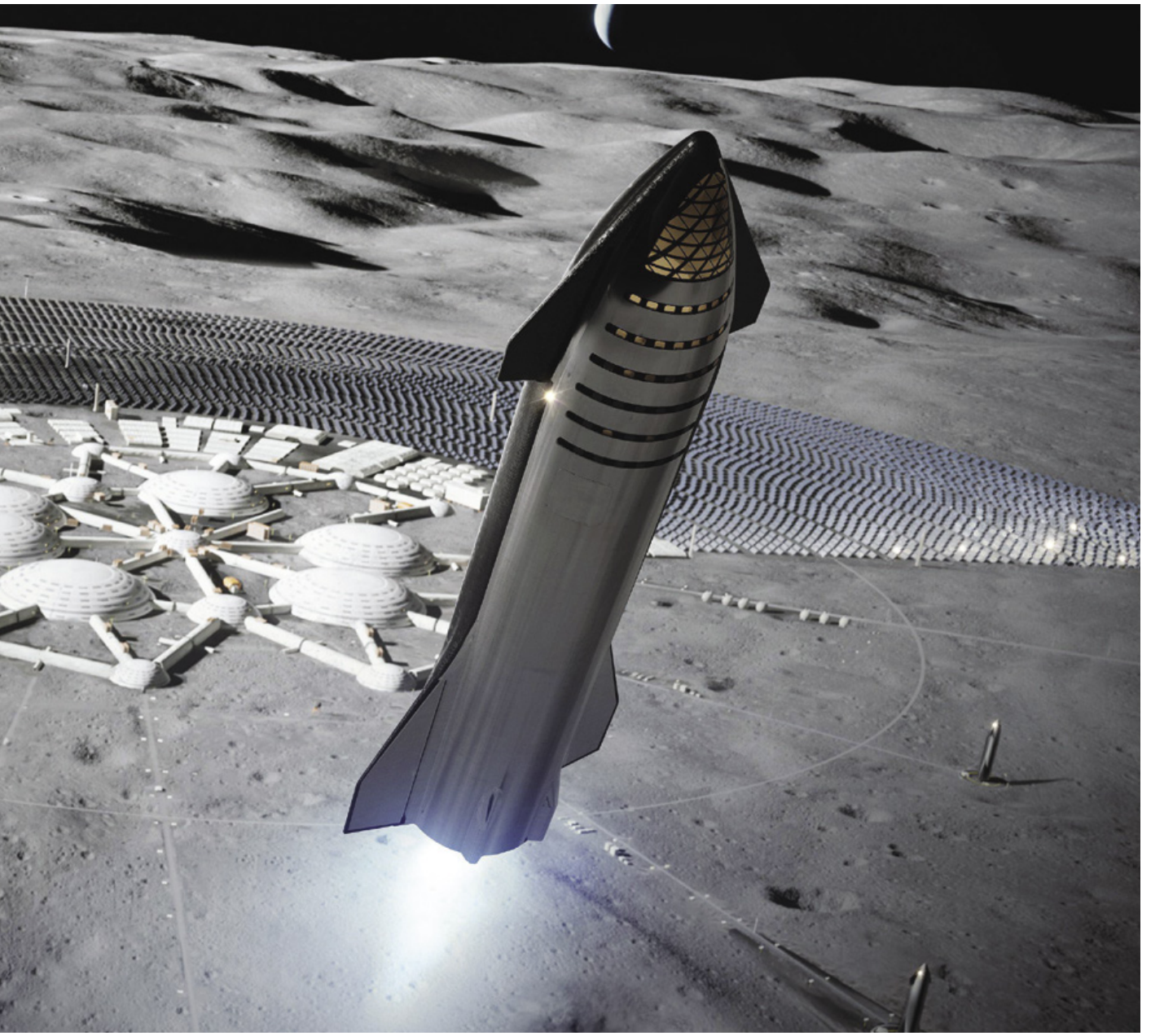

eyes for only one rocket: Starship. "Starship is not just an incremental change," says Jennifer Heldmann of the NASA Ames Research Center. "This is a significant paradigm shift."

INTO THE UNKNOWN

STARSHIP, BY ITS DESIGN, can be refueled by other Starship vehicles in Earth orbit. This means it could, hypothetically, carry a huge amount of mass around the solar system. "You could get a 100-ton object to the surface of Europa," SpaceX's CEO Elon Musk said in a public meeting of the National Academies in November 2021. That is a five times greater performance than the very best the SLS can offer, even in its final configuration with a kick stage. Starship is also forecast to be significantly cheaper, although whether it can hit Musk's optimistic projection of less than $10 million per launch remains to be seen. "If they get anywhere near that cost, it's kind of an analogue to a 747 and a shipping container all in one," says Robin Hague, former head of launch at the U.K. launch company Skyrora. "That's going to be used throughout the solar system."

With 1,000 cubic meters of usable volume, Starship is also big enough to fit the entire Eiffel Tower, disassembled (though not powerful enough to lift it into orbit). This gargantuan capability led Heldmann and her colleagues to publish a paper on what sort of equipment Starship could carry to the lunar or Martian surface. "Refilling Starship in orbit effectively resets the rocket equation, allowing for large payloads to be transported to the Moon and Mars," they wrote, a reference to the fact that the more mass you want to launch, traditionally, the more thrust you need on an exponential scale. Starship is not limited to these destinations, though. "It is not fine-tuned to either the moon or Mars," says

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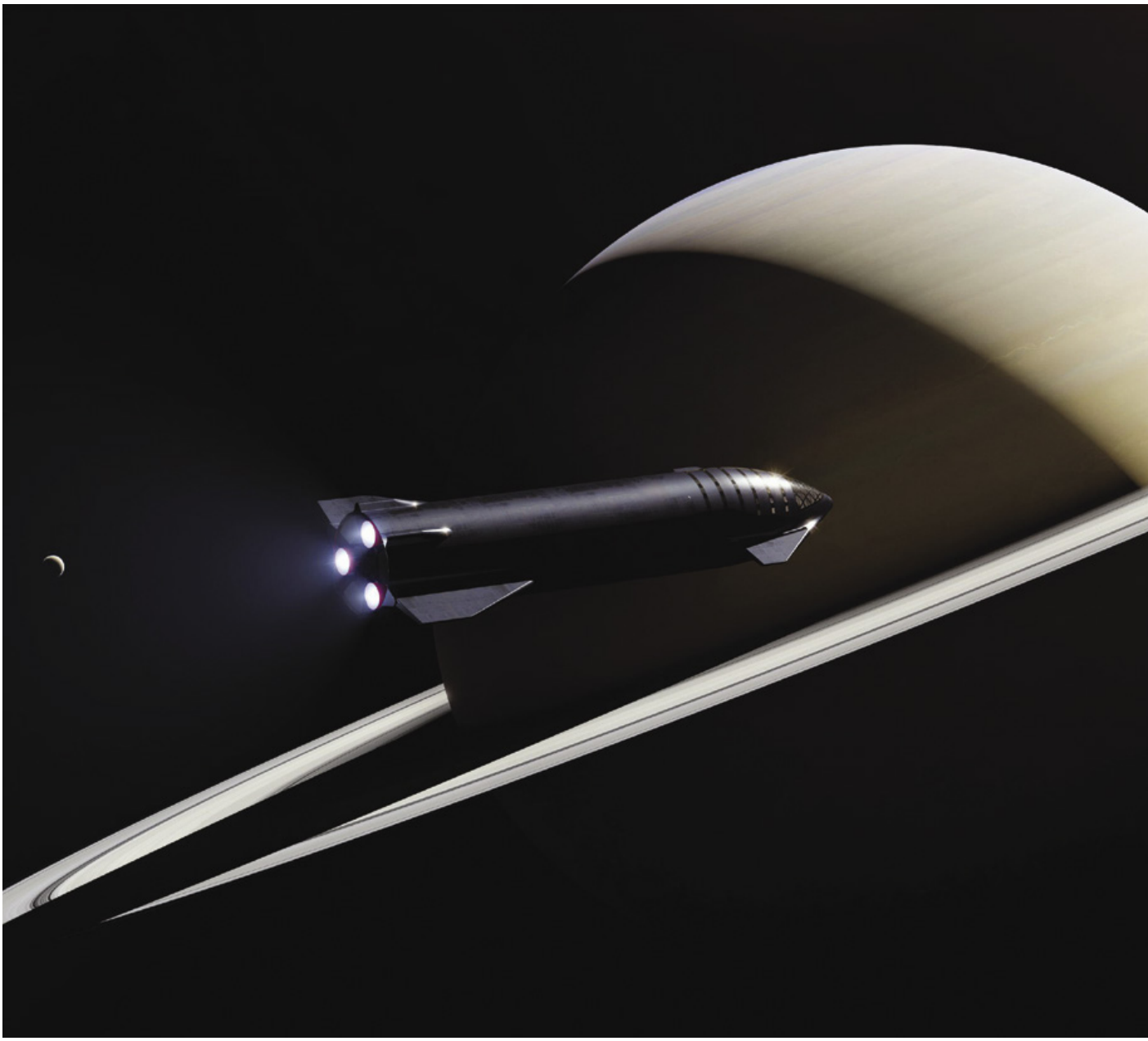

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Margarita Marinova, a former senior Mars development engineer at SpaceX. "The goal for Starship is to create this more generic, larger-scale exploration capability."

Ideas include launching full-size drills rather than pint-size versions. "You can put a 100-foot [30-meter] drill on the vehicle and then just deploy it," Heldmann says. "You don't have to try and fold it up. That's exciting because you can drill down into ice on Mars, which is very important for sustaining human exploration and also the search for life." Starship could conceivably also offer a two-way delivery service, returning vast quantities of material to Earth from these and other worlds. "We've always been very cautious about the samples we return because we've been limited by the amount of mass," Heldmann says. "With Starship, you can just load up that vehicle with rocks and ice and whatever else you find."

Meanwhile Martin Elvis of the Harvard-Smithsonian Center for Astrophysics and his colleagues have written a white paper on how Starship's unique capabilities could be used to launch a wide variety of next-generation space telescopes to revolutionize astrophysics. One idea is an extension of the Event Horizon Telescope, a "virtual" observatory on Earth used in 2019 to capture the first-ever image of a supermassive black hole. In a single launch, Starship could send a stack of six-meter telescopes into space, allowing for the creation of a much larger virtual telescope. That could provide views of "thousands of supermassive black holes" found at the centers of galaxies like our own, Elvis says.

Starship—and the SLS—could also launch a large telescope custom-built to image Earth-like exoplanets around other stars, as recommended to NASA by the National Academies' Astronomy and Astrophysics Decadal Survey in November 2021. "The diameter of mirror the Decadal report suggested was six meters, which

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A SPACEX STARSHIP is shown approaching Saturn in this illustration.

is about the same as the JWST," Elvis says. But with a super-rocket's large payload fairing, such a mirror could be monolithic, without any need to unfold and deploy in space, probably resulting in major cost savings and a speedier path to the launchpad. "That would simplify the design dramatically," Elvis says.

A CAVALCADE OF ROCKETS

THE SLS AND STARSHIP are not the only options for future heavy exploration of the solar system. The Washington State–based company Blue Origin, founded by Jeff Bezos, is working on a reusable rocket called New Glenn that it says could loft 45 metric tons into Earth orbit. And New Glenn's successor New Armstrong is expected to be even more powerful. Both Blue Origin rockets could play a role in the scientific exploration of the solar system, although their true capabilities are unknown. China, meanwhile, is working on its own superheavy rocket called the Long March 9 to transport humans and machinery to the moon and Mars as early as the 2030s. It is touted as being able to lift as much as 140 metric tons to Earth orbit, says Andrew Jones, a space journalist who closely follows the Chinese space program.

"They're set on a super-rocket," Jones says. "We're seeing China become more and more interested in planetary exploration—and even looking beyond the boundaries of the solar system." That latter notion is also something the U.S. is considering with a proposed mission called Interstellar Probe, which may need to rely on the SLS or a similarly sized rocket to reach its full scientific potential. "Without SLS or larger launch vehicles, you could not do the Interstellar Probe as intended," says Runyon, who is planetary science lead for the proposal.

Some have wondered if this new generation of superheavy-lift vehicles is needed at all and whether multiple smaller launchers could send spacecraft components into orbit for subsequent assembly by astronauts or robots. That same modular approach could also be used to launch rocket fuel to fill orbital depots, potentially offering similar enhancements to in-space capabilities without the need for a giant rocket. This fuel-depot idea is rumored to have been much maligned by NASA in the early days of the SLS's development because it undercut the rationale for the program in the first place. George Sowers, former chief scientist at the United Launch Alliance (ULA) and now at the Colorado School of Mines, says he had worked on such ideas at ULA a decade ago but was asked to stop. "It got really political," he says. "We were basically told to sit down and shut up." NASA would later change its tune, and the agency has since selected ULA and others to demonstrate in-space refueling and depot technology.

Daniel Dumbacher, now executive director of AIAA and formerly part of the leadership at NASA that selected the SLS for development in 2010, says other options were considered. The agency looked at a variant of the SLS that used kerosene rather than the liquid hydrogen and oxygen version that was opted for in the end. That system also used smaller rockets launched in tandem like ULA's Atlas V or SpaceX's Falcon Heavy. But ultimately, such an option was deemed too complex and expensive. "We did look at an option of what it would take if we utilized Atlas V– and Falcon Heavy–class vehicles," Dumbacher says. "It was down-selected out because it had negative effects on mission reliability and was more costly because of the number of launches required to execute the mission." More than 10 launches would have been needed to replicate a single SLS launch, he says.

There is no denying that the SLS is an expensive machine. Yet given its technological maturity, if costs can be brought down, it remains a promising choice for future scientific missions. Starship, meanwhile, represents something entirely new in space exploration. There is much that has yet to be proved, including the launch and landing of the giant rocket and its ability to refuel in space. But if those hurdles can be overcome, exploration of the solar system and the cosmos may be limited not primarily by rockets but rather by human imagination.

"There's a ton of excitement about what really high-performance rockets will enable," Runyon says. "The solar system really opens up in a way that's never been done before." SA

Jonathan O'Callaghan is a freelance journalist covering commercial spaceflight, space exploration and astrophysics.

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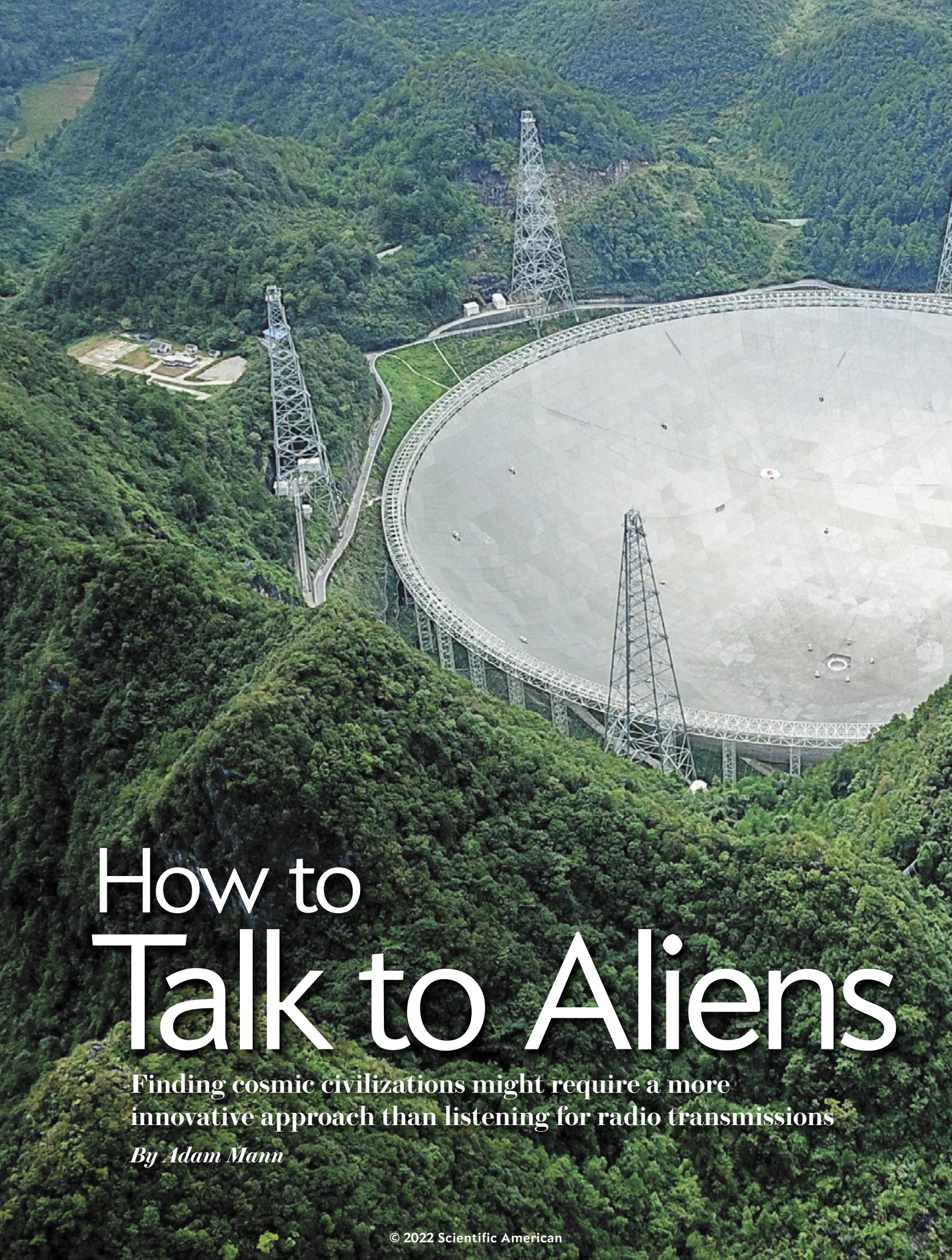

How to Talk to Aliens

Finding cosmic civilizations might require a more innovative approach than listening for radio transmissions

By Adam Mann

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AERIAL PHOTOGRAPH, taken on August 27, 2019, shows the Five-Hundred-Meter Aperture Spherical Radio Telescope (FAST) in China's southwestern province of Guizhou.

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THE ENDEAVOR KNOWN AS THE SEARCH FOR EXTRATERRESTRIAL INTELLIGENCE (SETI) has long relied on radio telescopes to listen for broadcasts from potential alien callers. Yet in an expansive galaxy such as ours, how can we ever be sure that we have tuned in to the right station?

A model simulating contact across the Milky Way suggests—perhaps unsurprisingly—that unless our galaxy is dense with long-lived intelligent species, the odds of stumbling across a signal are low. Yet the findings, which were published in 2020 in the *International Journal of Astrobiology,* also point out that the probability of interaction could be greatest at the moment when a novel communication technology first comes online.

Along with providing fodder for imaginative scenarios—we flip the switch on some new listening device and, *voilà,* receive a transmission from E.T.—the results might encourage would-be alien hunters to innovate. Research efforts dedicated to discovering and developing new methods to communicate across cosmic distances may ultimately offer greater chances of making contact than long programs that use a single technology.

For Marcelo Lares, the research began with a challenge. An astronomer at the National University of Córdoba in Argentina, Lares ordinarily works on data-rich statistical analyses involving stellar populations, the large-scale structure of the universe and gravitational-wave events.

Thinking about aliens offers no such informational abundance. "We have just one observation, which is that Earth is the only known planet with life," Lares says.

Scientific speculations about otherworldly life, intelligence and technology often rely on the Drake equation. This mathematical framework was first written down by astronomer Frank Drake in 1961. It estimates the number of communicating species by looking at the fraction of stars in the galaxy with planets, the percentage of those planets that develop life and the odds that such living creatures will grow curious about, and capable of, making interstellar contact with other beings.

Lares and his collaborators wanted something simpler. Rather than hazarding guesses about the unknowns involved in life's genesis and the development of intelligence and technology, they created a model that had essentially three parameters: the moment when communicating species "awaken" and begin broadcasting evidence of their presence, the reach of such signals and the lifetime of any given transmission.

Ou Dongqu/Alamy *(preceding pages)*

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The resulting arrangement places a bunch of nodes—or intelligent message creators—at random throughout the Milky Way, where they sometimes broadcast and sometimes do not. "It's like a Christmas tree," says astronomer José Funes of Catholic University of Córdoba, one of Lares's co-authors. "You have lights going on and off."

The team ran more than 150,000 simulations, each time with a different set of assumptions about these basic parameters, to see which scenarios favored interstellar contact. A galaxy full of technological aliens announcing themselves produced far more interactions than one where species were separated by vast distances or great amounts of time.

Such conclusions might not necessarily be shocking. "It's just a statistical way of saying, 'If you want to increase your chances of contact, you need greater numbers [of communicators] or have them last a long time,'" says planetary scientist Ravi Kopparapu of the NASA Goddard Space Flight Center, who was not involved in the work.

But Lares counters that quantifying our intuitive conceptions with mathematical models can be valuable, if only to serve as a reality check on our basic understanding. The findings set a kind of upper limit on the probability of contact under different circumstances, he adds.

In each case, the simulations showed that the odds of interstellar interaction are by far the largest just at the moment when a species "awakens" and figures out the right way to communicate. That result happens because other nodes will have already come online and presumably found one another, essentially creating a large branch of "lit up" Christmas tree lights and increasing the chances of stumbling across this broadcasting network. But if the lights are flashing out of sync with one another or at vastly different times—a situation that is analogous to using the wrong contact technology or being separated by large time spans—intelligent species might never find one another.

After SETI's historically preferred contact technology—radio waves—became commonly available in the early part of the 20th century, some discoveries were even initially thought to be alien transmissions. And in the 1960s British astronomers Jocelyn Bell Burnell and Antony Hewish originally called the first detection of a pulsar, a rapidly spinning stellar corpse, LGM-1 for "little green men" because the source's pulses seemed too regular to be natural. Yet humanity has slowly been sending out fewer radio emissions over the decades as we have upgraded our technology to wired and fiber-optic cables, which has lessened the chances that aliens might stumble across our leaking transmissions.

The study's authors see their findings as one possible answer to the Fermi paradox, which asks why we have not found evidence of intelligent aliens, given that in the long history of our galaxy, some technological species could have arisen and sent dispatches of its existence across space by now. The work suggests this absence is not very meaningful—perhaps E.T. is too far away from us in space and time or is just using some calling card that is unknown to us.

At the heart of the research is also an attempt to step away from some of the human-centric biases that tend to plague speculations about alien others. "It's very difficult to imagine extraterrestrial communication without our anthropomorphic way of thinking," Funes says. "We need to make an effort to exit from ourselves."

Kopparapu concurs with this assessment. "Unexpected discoveries come from unexpected sources," he says. "In our common-knowledge thinking, we are in a box. It is hard for us to accept that there could be something else outside it."

SETI's focus on radio waves developed under particular circumstances during a small slice of human history. Although the undertaking has sometimes tried other means to discover intelligent aliens, such as looking for high-powered laser beams or evidence of massive star-encircling artificial structures called Dyson spheres, any search still seemingly remains just as limited by the human imagination as it is by fundamental physics.

> "It's very difficult to imagine extraterrestrial communication without our anthropomorphic way of thinking."
> —José Funes *Catholic University of Córdoba, Argentina*

Yet looking for something as potentially fantastical as another cosmic culture requires the convergence of many disciplines, including physics, biology and even philosophy, Lares says. The effort to consider more creative messages, such as ones made by neutrinos, gravitational waves or phenomena that science has yet to discover, can help break down our parochial conceptions and give us a fuller understanding of ourselves.

Despite the small odds of contact, Lares is hopeful that attacking the problem in many ways will one day pay off. "I think that a SETI search is a high-risk bet," he says. "The probability of success is actually very low. But the prize is really very high." SA

Adam Mann is a journalist specializing in astronomy and physics. His work has appeared in *National Geographic*, the *Wall Street Journal*, *Wired*, and elsewhere.

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Eyes on the Neighbors

A privately funded telescope called Toliman will seek habitable worlds in our nearest neighboring star system, potentially sparking a new wave of exoplanetary exploration

By Jonathan O'Callaghan

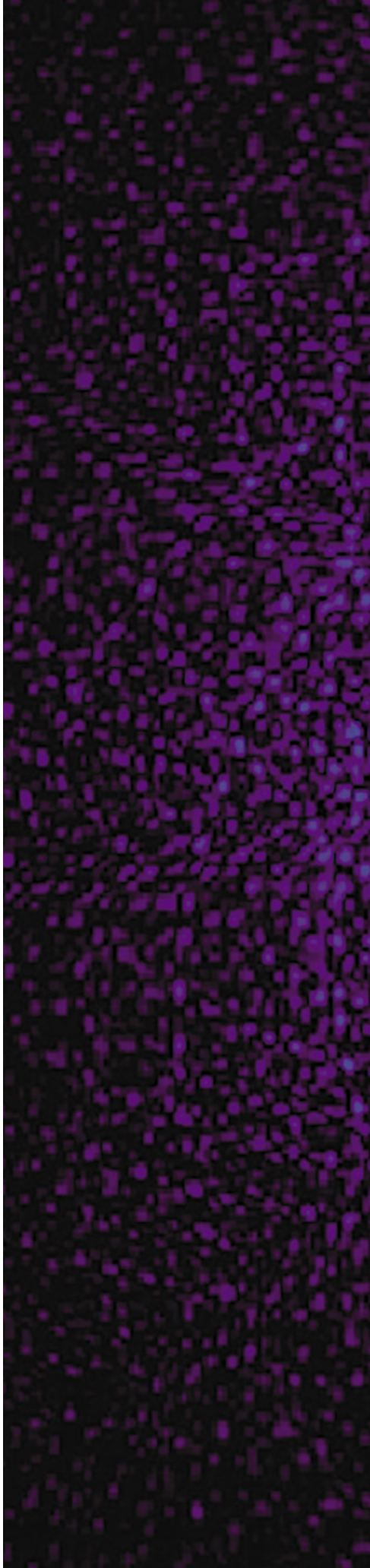
Do any habitable worlds exist in the closest stellar system to our own, Alpha Centauri? For years scientists have struggled to answer this question, unsuccessfully seeking to pierce the overpowering glare of the two sunlike stars, Alpha Centauri A and B, to see signs of orbiting planets (a third member of the system, the red dwarf star Proxima Centauri, is already known to possess at least one companion).

The scientific payoff for unveiling Alpha Centauri's planetary retinue could be tremendous. At little more than four light-years away, a mere fraction of a stone's throw in cosmic distances, these stars are tantalizingly close—right on our celestial doorstep. Any planets there would be prime targets for further study, but Earth-like worlds potentially harboring life would be the grandest of all. Now a group of scientists plans to conduct a search for such worlds like never before, using a privately funded telescope to revolutionize our knowledge of Alpha Centauri. "We have this unique opportunity to reveal if there is a 'habitable zone' planet in the system," says Olivier Guyon of the University of Arizona, part of the telescope's team. "This is something that has never been done before."

This relatively low-cost telescope, called Toliman, has secured funding of more than $500,000 from the Australian government to continue development, the team announced on November 16, 2021. Led by Peter Tuthill of the University of Sydney, who with his colleagues first devised the Toliman concept several years ago, the telescope has previously received backing from the NASA Jet Propulsion Laboratory, space engineering firm Saber Astronautics in Australia, and the California-based Breakthrough Initiatives, funded by tech billionaire Yuri Milner.

The small shoebox-sized telescope is being designed with a specific goal in mind: look for planets in the Alpha Centauri system, specifically any in its habitable zone, the starlight-warmed region in which liquid water could persist on a rocky world's surface. It will do so in a way no other telescope can yet match. The aim is to finish and launch the telescope into Earth's orbit by 2023, ready to begin its search from space. "This announcement is fantastic," says Sara Seager of the Massachusetts Institute of Technology, a planet hunter unaffiliated with the project. "It's just fantastic to see private foundations accelerating our search to find another Earth."

Many efforts have been made to find



Peter Tuthill/University of Sydney

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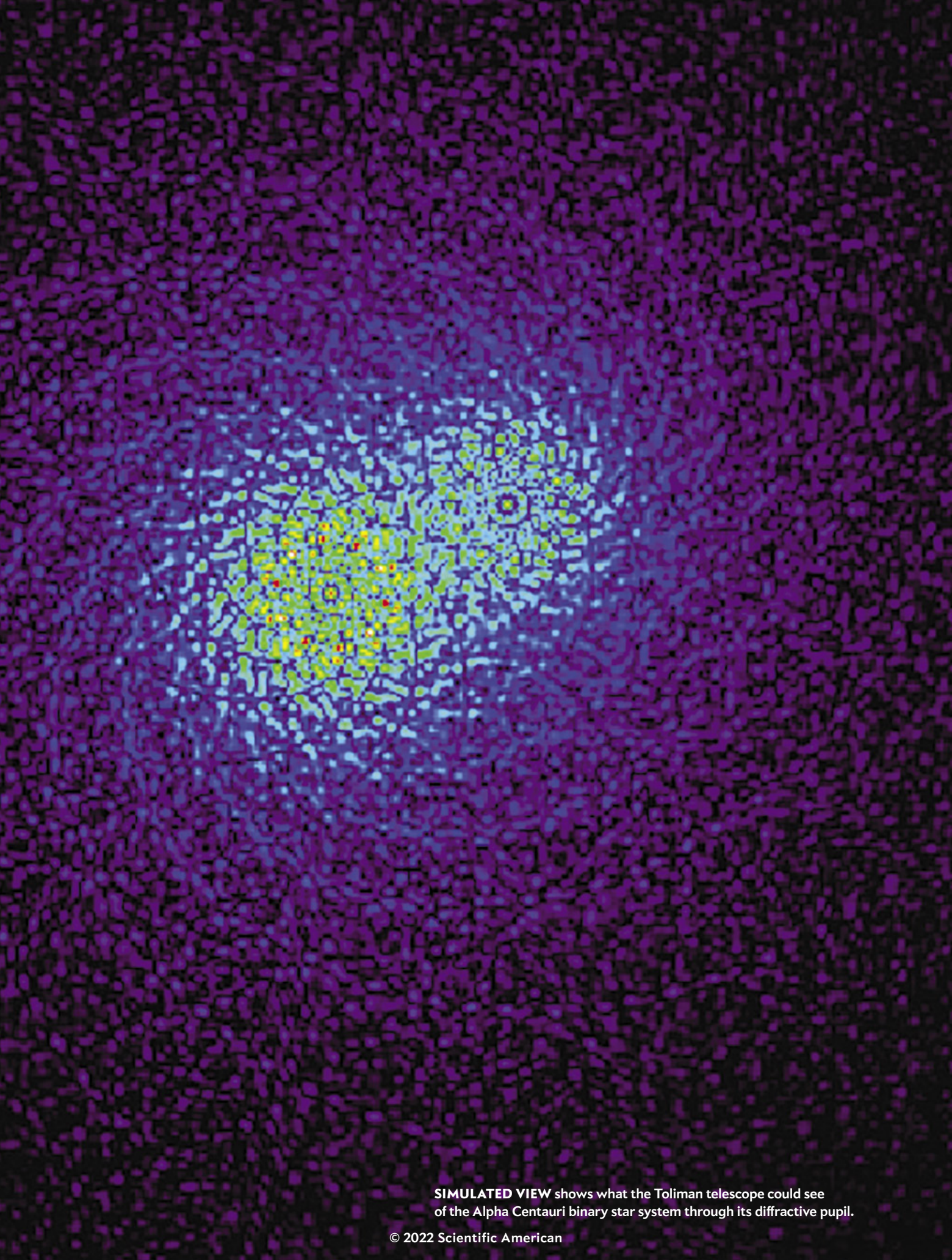

SIMULATED VIEW shows what the Toliman telescope could see of the Alpha Centauri binary star system through its diffractive pupil.

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Alpha Centauri's planets, with varying levels of success. In 2012 scientists thought they had found a planet orbiting Alpha Centauri B, dubbed Alpha Centauri Bb, but in 2015 other researchers seemingly ruled out the planet's existence. Investigations of Proxima Centauri have proved more fruitful, revealing a possibly Earth-sized world dubbed Proxima b; another planet—Proxima c—has also been hinted at. Early in 2021, meanwhile, a possible Neptune-sized world may have been found orbiting Alpha Centauri A.

Toliman, an ancient Arabic name given to Alpha Centauri that, in this case, also stands for the Telescope for Orbital Locus Interferometric Monitoring of our Astronomical Neighborhood, is designed to hunt for planets around Alpha Centauri A and B. Parts of the telescope are "already under contract" for construction, Tuthill says, and a precursor to the mission to test the technology, called Toliboy, was launched in 2021 on the CUAVA-1 satellite to the International Space Station. Lab testing and simulation work has been underway at the University of Sydney on the technologies for Toliman, Tuthill says, with the team now working on a full-scale prototype. Although some aspects of the mission are yet to be ironed out, such as its rocket ride to space and its station in Earth orbit, the technology itself is largely ready to go. "The components of this [telescope] are fairly mature," says Guyon, who is also chair of the Breakthrough Watch project within Milner's Breakthrough Initiatives, which has a goal of finding planets around Alpha Centauri and other nearby stars. "They can be made today."

The telescope's major trait is to make use of the binary nature of Alpha Centauri A and B, which are separated by slightly more than the Uranus–sun distance, to probe the existence of planets in either star's habitable zone. The telescope will use a technology known as a diffractive pupil to study the stars, a transformative approach that employs "a bit of an optical trick," Tuthill says. Rather than taking very high-resolution images of the stars, the 12-centimeter-wide telescope will spread the light from the stars into thousands of pixels, creating an elaborate patterned image within which a kind of photonic fingerprint of each star's spatial position on the sky can be seen. From these data, the scientists hope to see minuscule shifts in each star's position caused by the gravitational tug of any orbiting planets. This task—a so-called astrometric measurement—is made much simpler by the presence of two stars rather than one, allowing the distance between the two stars to be more accurately measured. "Alpha Centauri is just a sitting duck for this particular technique," Tuthill says. "It's almost like the universe put it there for this particular mission."

Two years' worth of astrometric observations with Toliman should allow the team to tease out the presence—or absence—of planets orbiting at a similar distance to Earth, that is, within the habitable zone of Alpha Centauri A or B. But astrometry's greatest power is arguably its ability to give astronomers accurate measurements of any newfound planets' masses by assessing the strength of each world's gravitational pull on the stars. Most other planet-detection techniques yield only estimates of mass, muddying the observational distinction between, say, a gas-shrouded "mini-Neptune" and a more Earth-like rocky orb.

There are, however, minor downsides: Toliman's studies will not initially reveal which of the two stars any such planets orbit. But we would know with near certainty if any potentially habitable Earth-mass planets exist in the system. "We'll be able to tell if it's a habitable zone or an Earth-mass planet," Tuthill says. "If we detect something, we hope that provokes a bit of a gold rush, and people will go after this with more sophisticated missions."

The Toliman mission heralds two interesting developments in exoplanet science. The first is the use of private funds, rather than the sole backing from space agencies and other governmental institutions, to conduct space science off-world, focusing on a chancy endeavour with no guarantee of success. "These types of high-risk missions have been really hard to sell to public funding agencies because there's a chance there is no planet in the Alpha Centauri system," Guyon says, yet the potential rewards are great. "If there is something, we would know the nearest star system to us has a [potentially] habitable planet. It would completely change plans for agencies." The project also signals a much sought after shift, from finding thousands of exoplanets over the past two decades to studying certain star systems in lavish detail. "We've had this trend of finding so many planets," Seager says. "But some of us in the community are ready to focus on individual stars."

Emily Rickman of the Space Telescope Science Institute in Baltimore says the technology behind the Toliman telescope is "exciting" given the proximity of these stars to our own. "Finding any promise of alien life in our celestial backyard would be a really big deal," she says. Even if it does not detect anything, the mission will place useful constraints on the Alpha Centauri system. "If nothing is found, that will either tell us there's something extremely tiny and close to the star that we cannot see or there's nothing around those stars," she says, which would be an intriguing and valuable result all on its own.

Tuthill says there are secondary targets that could be examined after Alpha Centauri, also with the Toliman telescope, namely, other nearby binary systems such as 61 Cygni, which is 11 light-years away. But these other stars are not sufficiently close to afford as much precision, and thus they could be surveyed only for heftier, probably less habitable, worlds. "We would hope to get down to super-Earths or Neptunes" in mass for detecting planets around those other stars, Tuthill says.

For now, however, Alpha Centauri is the primary goal, with the possibility of a titanic discovery on the horizon. Within just a few years we may know if one or more potentially habitable Earth-mass worlds exist there, so near at hand that we might seek not only to study them with telescopes but also to visit, reaching out via robotic probes launched across the interstellar depths. Proposals for such voyages already exist, including Breakthrough Watch's more limelight-illumed kin, Breakthrough Starshot, a sister project from the Breakthrough Initiatives aiming to send miniaturized spacecraft at perhaps a tenth the speed of light toward Alpha Centauri. Toliman would provide key data in support of such a multidecadal mission.

"We know there's at least one planet in the system, Proxima b," says Pete Worden, executive director of the Breakthrough Initiatives. "If we ultimately confirm that Alpha Centauri A and B do not have potentially life-bearing planets, then I would probably focus on Proxima." If everything goes to plan, we may not have long before we find out. SA

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Sun Spots Alien Earths

In the far future, we could reveal detailed views of distant worlds by turning our home star into a gravitational lens

By Allison Gasparini

WE NOW KNOW OF MORE THAN 5,000 EXOPLANETS beyond the solar system. What we really understand about each of these worlds, though, is barely anything at all. Most of them have been seen only indirectly from their shadows as they cross in front of the stars they orbit. The few that researchers have managed to actually take a picture of—that is, to directly image using light emanating from the planets themselves—appear as little more than monochromatic dots even with the very best current telescopes. And so far all of those directly imaged worlds are among the brightest, largest and least Earth-like exoplanets known.

The far future may be a different matter. How detailed could a picture of a distant exoplanet be—especially one that is small and rocky like Earth? The answer is that someday astronomers could obtain images that reveal continents, clouds, oceans, ice caps and even vegetation on some remote Earth-like world orbiting an alien star.

The problem is that the most powerful telescope for this task can't be built—not exactly, anyway. Instead it must be conjured into existence using the tenets of Einstein's general theory of relativity to transform our sun into a star-sized magnifying glass. Albert Einstein's key insight—that gravity can be understood as the curvature of spacetime—means that stars and other massive objects act as natural "gravitational lenses" that warp and amplify the light from background objects.

Astronomers today routinely use galaxies and galaxy clusters as gravitational lenses, but the prospect of using this technique for our sun poses so many challenges that few researchers have taken it seriously. Most notably, the approach requires precisely positioning a conventional telescope—something like Hubble, for instance—at the point where any given target's lens-amplified light comes to a focus. For the sun, those focal points are found at the extreme outskirts of the solar system—at least 14 times farther out than Pluto.

Now a new study by astronomers at Stanford University shows that a simplifying shortcut could exist for the still arduous task of imaging exoplanets by using our sun as a cosmic telescope. The study, published in the *Astrophysical Journal,* suggests astronomers could eventually achieve exoplanet imaging with a resolution 1,000 times greater than that of the Event Horizon Telescope, which has been used to capture the historic first images of supermassive black holes. "It's just neat to think of this as kind of the ultimate end game of the process of studying exoplanets," says Stanford astrophysicist Bruce Macintosh, who co-authored the paper, "or at least the end game short of actually visiting them."

Alex Madurowicz, Macintosh's co-author and graduate student, first fed real satellite images of Earth into a computer model that reduced our world to how it might appear if it were seen from afar through a stellar gravitational lens. In most circumstances, the resulting image would be an "Einstein ring"—a distorted, circular smear produced by the planet's light curving around the lensing star. Earlier work by another researcher, Slava Turyshev of the NASA Jet Propulsion Laboratory, had shown that correcting those distortions would require methodically moving a light-gathering conventional telescope back and forth within the focal region at the solar system's edge. The resulting pixel-by-pixel scan of the planet's warped projection, somehow choreographed from Earth upward of 80 billion kilometers away, could

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THE BLUE HORSESHOE is in fact a distant galaxy that has been both magnified and warped by the nearer red galaxy through gravitational lensing.

ESA/Hubble and NASA

take thousands of hours and consume enormous amounts of fuel.

Madurowicz and Macintosh realized that this harsh calculus could change, however, given that the sun is slightly oblong rather than perfectly spherical. That minor detail means that if the target exoplanet aligns perfectly with the sun's equator as seen from the focal-region telescope, the product is not an Einstein ring but a "cross"—four asymmetrical copies of the planet around the sun's perimeter. Madurowicz found that if this asymmetry is exploited, the scanning process to reconstruct a target exoplanet's undistorted image can be eliminated. "You don't have to move [your telescope] around inside the image," he says. "You can just stay in one spot."

Turyshev, who was not part of this latest study, is skeptical that the painstaking process of scanning he first described can actually be eliminated. The idealized technique for image reconstruction that Macintosh and Madurowicz propose, he says, would have to overcome possible interference arising from the brightness of our sun and its seething outer atmosphere, known as the corona. "It would be nice if the sun would just be dark, right?" Turyshev says. But it is not, of course, and even the best

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Astronomers don't even know if there is another world like our own out there at all. And direct imaging, it seems, is the only way to really find out.

equipment could not fully block a fraction of its light from trickling into a telescope, especially one staring directly at our star. "Their paper is wonderful, but it's a theory," he adds.

Even if the scanning process could be eliminated, there are other limitations to consider as well. Each exoplanet targeted for solar gravitational lensing would probably require its own dedicated Hubble-like space telescope sent to and operated at the solar system's outer limits. For example, for such an observatory to image a second exoplanet just 10 degrees off from its original target, it would need to shift its position around the sun by more than 14 billion kilometers. "To use a solar gravitational lens, you need to line up the telescope, the sun and the planet extremely precisely," Madurowicz says. There would be no way for a single telescope to image more than one planet, or one star system with several interesting worlds, at a time.

This limitation is the reason Jean Schneider, an astronomer at the Paris Observatory, has his eye on a different, perhaps more feasible alternative to solar gravitational lensing: a hypertelescope. This broad concept envisions the detection of surface features of exoplanets through the use of space-based fleets of many meter-scale mirrors flying in formation to create virtual telescopes larger than any single one ever could be. Schneider agrees direct images of potential extraterrestrial vegetation would be "precious" and would provide insights unavailable through any other known method of remote observation.

Aki Roberge, an astrophysicist at the NASA Goddard Space Flight Center, points out that astronomers don't even know if there is another world like our own out there at all—"not just Earth-size," she says, "but Earth-like, with oceans, continents, an atmosphere and a biosphere." And direct imaging, it seems, is the only way to really find out.

A proposed observatory recommended in the National Academies of Sciences, Engineering, and Medicine's report *Pathways to Discovery in Astronomy and Astrophysics* for the 2020s, otherwise known as the Astro2020 Decadal Survey, may offer the best near-term hope of giving Roberge and her peers the answers they need. The survey serves as a once-a-decade road map guiding U.S. astronomy. And topping its latest road map is a concept for a space telescope with a mirror more than six meters wide, something of a "super Hubble" tuned for gathering optical, infrared and ultraviolet light that is intended for launch as soon as the early 2040s.

According to Astro2020's recommendations, one of the core capabilities of such a telescope would be directly imaging a diversity of exoplanets with the key objective of studying their atmospheres to make better guesses about their environmental conditions. From there, astronomers might determine whether the chemical necessities or by-products of life as we know it—water, organic compounds, free oxygen, and so on—exist on any of the targeted worlds. The fuzzy blobs that might be imaged by this proposed telescope could be the first small step toward truly knowing an exoplanet's potential to harbor life. Only after such a mission, most astronomers say, could we make the giant leap of building a hypertelescope or exploiting the solar gravitational lens to get detailed surface images. "We have a path to the 2040s. After that, it's the Wild West," Roberge says.

Despite the far-out nature of the solar gravitational lens, Turyshev, Macintosh and Madurowicz are of one mind: thinking about its possibilities now is worthwhile. Already advances in solar sails and other unconventional propulsion technologies offer the possibility of expediting the requisite journey to the solar system's outermost reaches. The challenges remain daunting, but using our star as the ultimate telescope may be closer to reality than anyone now suspects. By anticipating the theoretical and practical limits of the approach, when—or if—it finally lies within our grasp, the question will not have to be "Can we do this?" but rather "What planets should we image?" SA

Allison Gasparini is a science writer who has written for *Forbes*, *Science News*, NASA, Brookhaven National Laboratory, the American Institute of Physics, Stanford University, and more.

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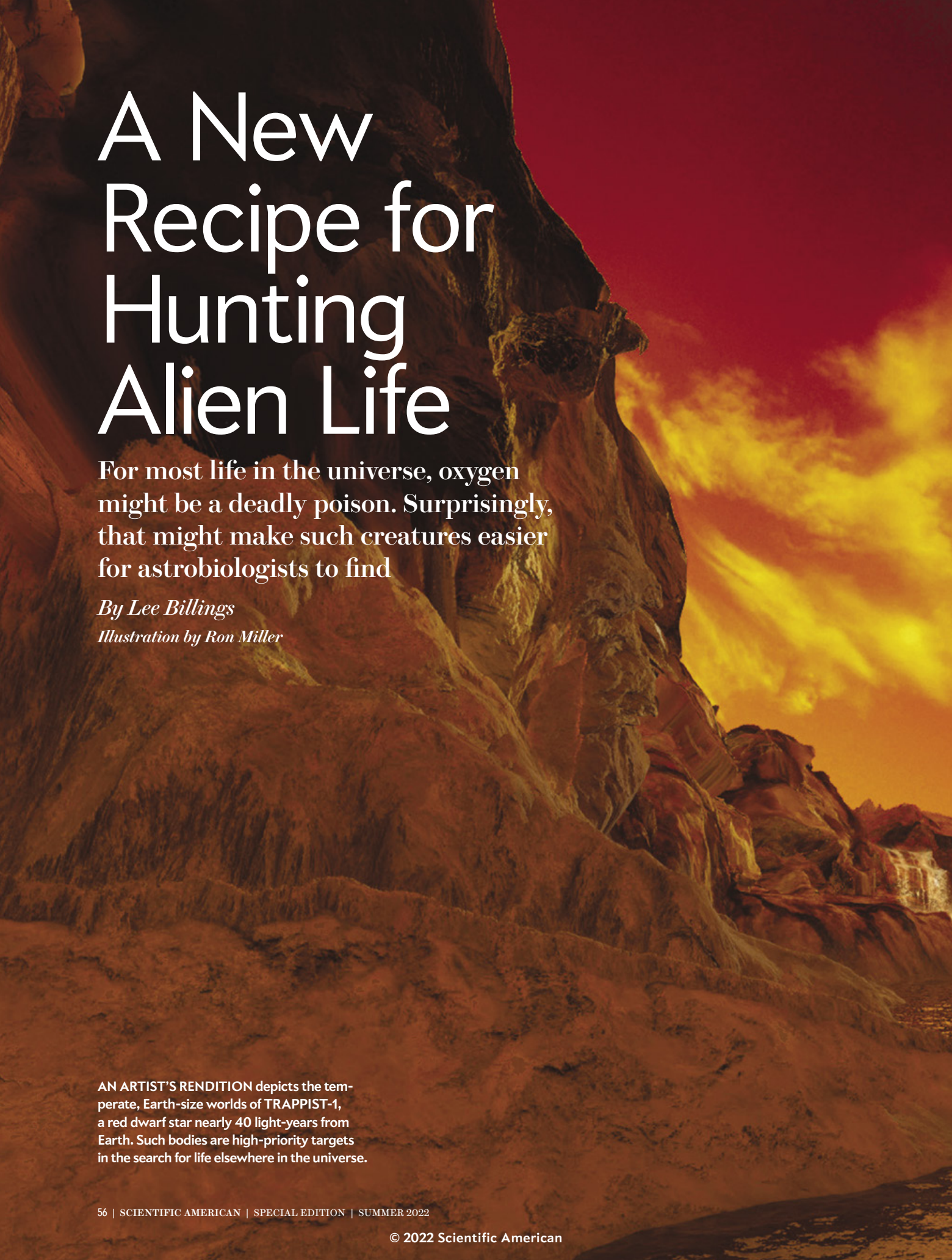
A New Recipe for Hunting Alien Life

For most life in the universe, oxygen might be a deadly poison. Surprisingly, that might make such creatures easier for astrobiologists to find

By Lee Billings

Illustration by Ron Miller



AN ARTIST'S RENDITION depicts the temperate, Earth-size worlds of TRAPPIST-1, a red dwarf star nearly 40 light-years from Earth. Such bodies are high-priority targets in the search for life elsewhere in the universe.

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IMAGINE STEPPING INTO A TIME MACHINE, ONE THAT COULD TRAVERSE NOT ONLY billions of years but also countless light-years of space, all in search of life in the universe. Where would you find most of it, and what would it look like? The answer—or at least scientists' best guess—might surprise you.

You might think most life out there would be like what we see on Earth today: grasses, trees and frolicking animals all orbiting yellow stars on watery worlds under blue, oxygen-rich skies. But you would be wrong. Astronomers conducting a galactic census of planets in the Milky Way now suspect most of the universe's habitable real estate exists on worlds orbiting red dwarf stars, which are smaller but far more numerous than stars like our sun. In part because of their immense numbers, such stars are in some respects easier for astronomers to study. Consider, for instance, the red dwarf star called TRAPPIST-1, just under 40 light-years away. In 2017 astronomers discovered that it is orbited by at least *seven temperate Earth-size planets*. A plethora of new observatories—chief among them NASA's recently launched multibillion-dollar James Webb Space Telescope—will soon begin studying the planets of TRAPPIST-1 and other nearby red dwarf planets for signs of habitability and life.

In the meantime, no one really knows, of course, what you would see if you visited one of these strange worlds in your planet-hopping time machine, but if they are at all like Earth, chances are you would find a planet dominated by microbes rather than charismatic megafauna. A fascinating study published in January 2018 explores what this curious fact might mean for alien-hunting astronomers. Co-authored by David Catling, an atmospheric chemist at the University of Washington, the study peers deep into our planet's history to devise a novel recipe for finding single-celled life on faraway worlds in the not too distant future.

Here on Earth most life is microbial, and a careful reading of the planet's fossil and geochemical record reveals it always has been. Organisms such as plants and animals—as well as the oxygen the plants produce and the animals breathe—are relative newcomers, having arisen only in the past half a billion years or so. Our planet seems to have spent the first two billion of the remaining four billion years of its history as a "slime world" ruled by methane-belching microbes for which oxygen was not a life-giving gas but rather a deadly poison. The emergence of photosynthetic cyanobacteria (named for their verdant hue, which comes from chlorophyll) defined the next two billion years and banished the "methanogen" microbes to dark places where oxygen could not go—subterranean caverns, deep muds and other smothered environments where they still exist to this day. The cyanobacteria gradually greened our planet, slowly filling the atmosphere with oxygen and setting the stage for today's familiar world.

Touching your time machine down on Earth at a random point in the planet's history, roughly nine times out of 10 you would find only single-celled life or algae and would risk suffocation in the oxygen-starved open air.

This creates a quandary for scientists hoping to use the Webb telescope, rather than a time machine, to seek out other life-bearing worlds. Molecules in a planet's atmosphere can absorb passing starlight, imprinting barcodelike signatures on the light that astronomers can then detect. Plentiful oxygen is one of the most obvious barcodes to look for in a planet's atmosphere across the light-years because it is one of the hardest things to make sans biology. In the parlance of astrobiologists, the highly reactive gas is a potent "biosignature" because in large concentrations it tends to be "out of equilibrium" with its surroundings. That is, oxygen tends to fall out of the air as a component of rust and other mineral oxides rather than lingering as a gas, so when it exists in abundance, something—photosynthetic life, in Earth's case—must be constantly replenishing it. But with our planet as their guide, astrobiologists are forced to acknowledge that oxygen may be the least likely thing they will ever see—genetic evidence suggests the complex oxygen-producing photosynthetic pathway pioneered by cyanobacteria is an extraordinary evolutionary innovation that appeared only once throughout the entire multibillion-year history of Earth's biosphere. One might expect, then, that any living "Earth-like" world scientists will ever gaze on through telescopes is likely to be anoxic, or lacking in oxygen. What other biosignatures should they seek instead?

Right now the best way to find an answer is to hop back into the time machine. Not a real one, of course, but rather a virtual voyager, a computer model that plumbs the otherwise inaccessible depths of Earth's anoxic past (or an alien planet's present),

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exploring the possible chemistry of gases in the atmosphere and ocean that could have occurred there. Use data from old rocks and other models to dial in your best guess for the environmental conditions of, for instance, the Earth circa three billion years ago, let the computer crunch the numbers, and see whether any obvious imbalances—potential biosignatures—pop out. This is exactly what Catling did, working with his colleagues Joshua Krissansen-Totton and Stephanie Olson.

Their "time machine" is essentially just a numerical approximation of an immense volume of air trapped in a large, transparent box with the open ocean at the box's base; the computer simply calculates how the constituent gases in the box should react and mix with one another over time. Eventually the interacting gases use all the "free energy" available in the box and reach equilibrium—a point where no further reactions can occur without more energy from outside, a bit like soda water that has lost its fizz. Comparing the cocktail of exhausted gases with the livelier mixture originally trapped in the box reveals precisely where and how the world's atmosphere was initially out of equilibrium. From first principles, this approach can replicate the most obvious example of atmospheric disequilibrium today on our planet—the presence of oxygen and traces of methane (the latter being the gentle exhalations of the once mighty methanogen biosphere). Simple chemistry shows these gases should not co-exist for long, and yet on Earth they do, offering a clear sign for any watchful alien astronomers that something lives and breathes on this particular pale blue dot. But for the ancient, anoxic Earth, the modeling shows something different.

"Our research provides the answer" to the question of how to find anoxic life on an Earth-like planet, Catling says. "Most life elsewhere is probably simple—like microbes—and most planets have probably not advanced to a stage of an oxygenated atmosphere. The combination of relatively abundant carbon dioxide and methane (absent carbon monoxide) is a biosignature of such a world."

Krissansen-Totton explains in more detail: "Having methane and carbon dioxide together is unusual because carbon dioxide is carbon's most oxidized state, and methane (composed of a carbon atom linked to four hydrogen atoms rather than any oxygen at all) is its least," he says. "Producing those two extremes of oxidation in an atmosphere at once is challenging to do without life." A rocky, ocean-bearing planet with more than 0.1 percent methane in its atmosphere should be considered a potentially inhabited planet, the researchers say. And if the atmospheric methane reaches levels of 1 percent or more? In that case, "potentially" doesn't cut it—such a world would "likely" be home to alien life.

Jim Kasting, an atmospheric chemist at the Pennsylvania State University, who is not affiliated with the study, says its results are "on the right track," even though "the idea that methane might be a biosignature in an anoxic atmosphere is not exactly new."

What is new, Catling and his co-authors say, is their robust treatment of how a methane-based biosignature would manifest itself and how it could be discerned from nonliving sources. According to their models, methane in the atmosphere of an anoxic Earth-like planet would typically react with the carbon dioxide that still filled the air, mingling further with another ubiquitous gas, nitrogen, as well as with water vapor to ultimately rain out as heavier compounds. Further calculations by Catling and his team concluded that no abiotic methane sources on a rocky planet could produce enough of the gas to counteract this process—whether it is volcanic outgassing from a planet's interior, chemical reactions in hydrothermal vents or even asteroid impacts. Only a thriving planetary population of methane-belching bacteria could account for the gas. And, most crucially, even if abiotic sources could come up with enough methane, they would almost inevitably produce a great deal of carbon monoxide as well—a gas poisonous to animals but positively delicious to many microbes. Thus, methane and carbon dioxide together, unaccompanied by carbon monoxide, on a rocky, ocean-bearing world would best be interpreted as an airtight sign of anoxic life.

This is good news for astronomers. The Webb telescope, it turns out, will be hard-pressed to directly discern oxygen in any potentially habitable planet it surveys during its mission. Just as your eyes can see visible light but not radio waves or x-rays, Webb's vision is tuned for the infrared—a portion of the spectrum ideal for studying ancient stars and galaxies but where oxygen's barcodelike absorption lines are rather slight and sparse. Consequently, some researchers have feared the search for life will have to wait for other, more capable telescopes many years or decades in the future. But although Webb cannot easily see oxygen, its infrared eyes might excel at glimpsing signs of anoxic life. According to Nikole Lewis of Cornell University, who worked on Webb as a project scientist at the Space Telescope Science Institute in Baltimore, the telescope can perform the simultaneous detection of methane, carbon dioxide and carbon monoxide in the atmospheres of some planets around red dwarf stars. And not just big, bloated gassy planets where we wouldn't expect life to exist anyway. "Webb can achieve the required precision to detect the molecules in the atmospheres of planets like those in the TRAPPIST-1 system," Lewis says.

> We expect that any living "Earth-like" world scientists will ever gaze on through telescopes is likely to be lacking in oxygen.

Even so, Lewis and others note that Webb may still struggle to fulfill the most crucial part of Catling's criterion—determining the relative abundance of each gas to pin down whether methane on some distant planet is the result of an erupting volcano or burping microbes. Consequently, Catling isn't holding his breath for Webb to find an anoxic biosphere on some red dwarf world.

"Webb probably has to get lucky to find life, but you never know, so this is potentially exciting for astrobiology," Catling says. "We want to make more people aware that there's more to looking for life than looking for oxygen." SA

Lee Billings is a senior editor for space and physics at *Scientific American.*

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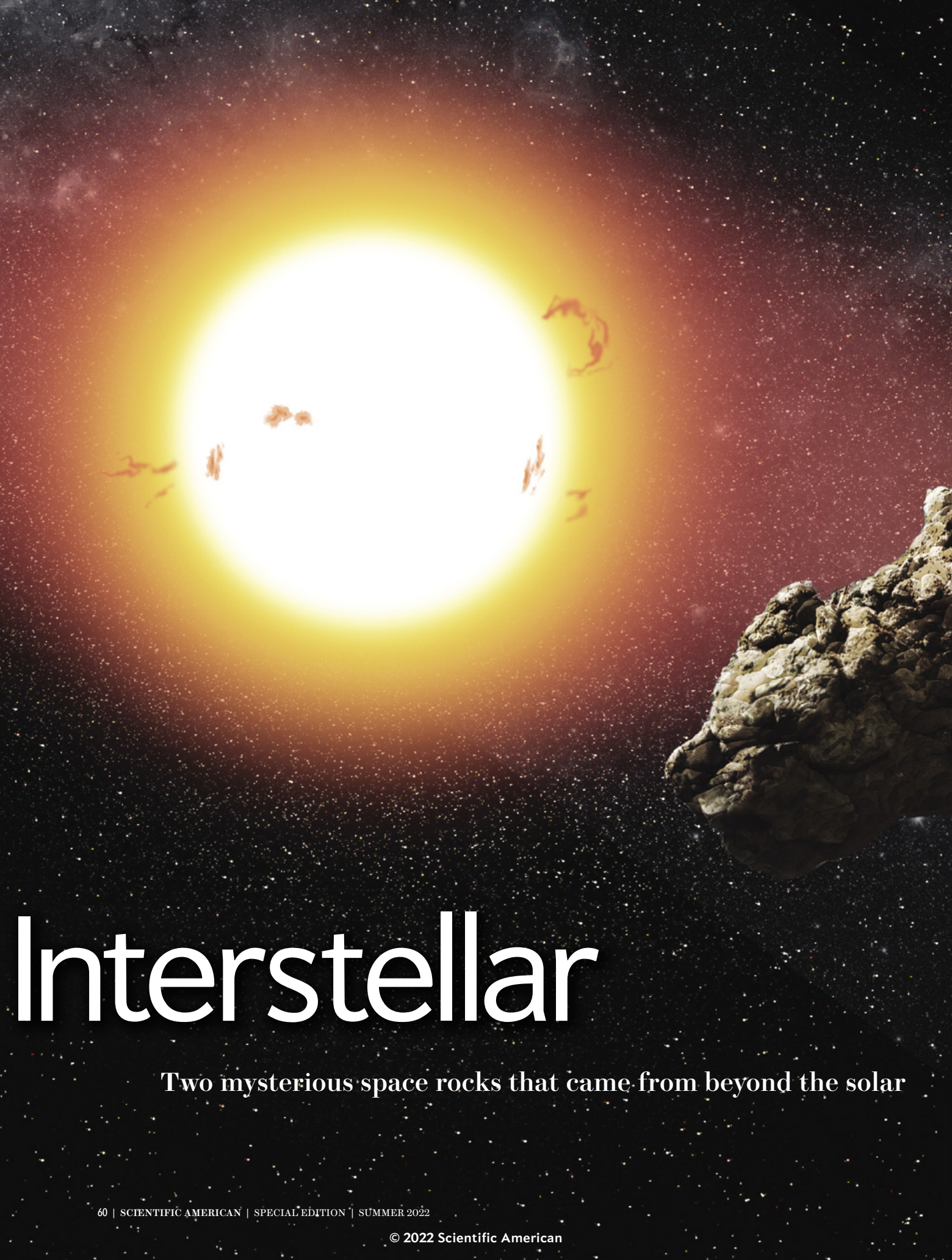

Interstellar

Two mysterious space rocks that came from beyond the solar

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1I/'OUMUAMUA, the first interstellar object ever observed in the solar system, passed close to Earth in 2017.

Interlopers

system have puzzled astronomers

By David Jewitt and Amaya Moro-Martín

Illustrations by Ron Miller

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LATE IN THE EVENING OF OCTOBER 24, 2017, AN E-MAIL ARRIVED containing tantalizing news of the heavens. Astronomer Davide Farnocchia of the NASA Jet Propulsion Laboratory was writing to one of us (Jewitt) about a new object in the sky with a very strange trajectory. Discovered six days earlier by Robert Weryk, then a postdoctoral researcher at the University of Hawaii, the object, initially dubbed P10Ee5V, was traveling so fast that the sun could not keep it in orbit. Instead of its predicted path being a closed ellipse, its orbit was open, indicating that it would never return. "We still need more data," Farnocchia wrote, "but the orbit appears to be hyperbolic." Within a few hours Jewitt wrote to Jane Luu, a long-time collaborator with Norwegian connections, about observing the new object with the Nordic Optical Telescope in Spain. Many other observatories around the world were simultaneously scrambling to spot it.

So began a new era in astronomy. Renamed C/2017 U1 (the "C" standing for "comet"), then A/2017 U1 (for "asteroid") and, finally, 1I/'Oumuamua, the object turned out to be the first body astronomers had ever seen in the solar system that originated outside it. The "1I" in its designation indicates its official status as the first-known interstellar object, and the name 'Oumuamua—"a messenger from afar arriving first" in Hawaiian—was proposed by Weryk and his colleagues, who had used the Pan-STARRS telescope on the Hawaiian island of Maui to make the discovery.

What first caught the observers' attention was the object's extreme speed relative to the sun. After accounting for the pull of the sun's gravity, 'Oumuamua had an excess speed of 26 kilometers a second (58,000 miles an hour). No interaction with a solar system body could generate such a kick, and the sun's gravity cannot capture something moving so quickly; 'Oumuamua had to have come from outside.

What kind of journey must this object have taken? From what we can tell, it could have been wandering the galaxy for hundreds of millions of years. Observations suggest that it came from the direction of the bright star Vega, in the constellation Lyra, although Vega would not have been in the same spot when 'Oumuamua was there roughly 300,000 years ago.

Although astronomers have long believed that interstellar bodies pass through the solar system, actually finding one was a big surprise. Only the year before, an exhaustive analysis by Toni Engelhardt, then at the University of Hawaii, and his colleagues concluded that prospects for identifying such an interstellar interloper "appear to be bleak"—they were thought to be just too small and faint for us to have much hope of finding them. But as we discovered more about 'Oumuamua, our surprise turned into utter bewilderment. Everything from its shape and size to its lack of cometlike properties ran counter to our expectations. If this was a typical visitor from the greater universe, we had a lot to learn.

ALIEN ARTIFACT OR COSMIC DUST BUNNY?

OBSERVATIONS FROM THE NORDIC OPTICAL and other telescopes soon showed that 'Oumuamua lacked a tail and a surrounding coma of sublimated dust and ice transitioning directly from solid to gas—the hallmarks of a comet. Rather, except for its unique orbit, 'Oumuamua looked like a rocky asteroid. Still, given that it had come from interstellar space, where the average temperature is only a few degrees above absolute zero, the absence of evidence for sublimating ice was startling. Water, the most abundant molecule in the universe after molecular hydrogen, should have been present.

And then there was the object's shape. Astronomers use the brightness of an asteroid as a measure of its size because bigger objects reflect more sunlight to Earth. 'Oumuamua's average brightness suggested a diameter of about 100 meters—quite small compared with most known asteroids. Indeed, if 'Oumuamua had been as far away as the asteroid belt, where most of the asteroids in our solar system reside, we never would have seen it. Instead we got lucky: it passed very close to us—about 60 million kilometers, which is only 40 percent of the average distance between the

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2I/BORISOV, the second-known interstellar visitor, was first spotted in 2019.

sun and Earth. The brightness of most asteroids, shaped like lumpy potatoes rotating in space, varies cyclically as they present alternately smaller and larger sides of themselves to Earth. Observing this rotation produces a "light curve," a plot of how the light changes that tells us the rotation period and gives us an estimate of the asteroid's proportions. In December 2017 scientists reported 'Oumuamua's light curve. At about eight hours its period was unremarkable compared with those of solar system asteroids. But whereas most asteroids vary in brightness by 10 to 20 percent as they spin, 'Oumuamua changed by an unprecedented factor of 10, suggesting an extraordinary needlelike shape that sometimes presented a large and bright surface and sometimes showed only a very narrow edge.

The object's resemblance in size and proportions to a large rocket—for example, the Saturn V, which measures about 110 meters by 10 meters—was hard to ignore. Indeed, discarded rockets orbiting the sun are occasionally rediscovered by astronomers surveying the sky for asteroids and comets, as was the case for 2000 SG344, a likely Apollo-program relic discovered in 2000. But the orbit of 'Oumuamua was too extreme for it to be a rocket from the 1960s. Could it be a rocket from another civilization? Incredible as it sounds, scientists could not immediately reject the possibility based on the available data.

While astronomers were pondering this conundrum, they got another surprise. In June 2018 Italian astronomer Marco Micheli of the European Space Agency and his colleagues reported measurements of the shape of 'Oumuamua's orbit, which revealed the action of a weak, rocketlike force pushing on the body in addition to the gravitational forces of the sun and planets.

So-called nongravitational forces are well known to exist in comets, arising from the asymmetric push of ices sublimating from the dayside of the comet's core. But 'Oumuamua is not a comet. And it showed no evidence that it was losing mass at all, which could have explained the force. Could it be that 'Oumuamua emitted only gas, which is harder to detect than comet dust? Possibly, but it would make 'Oumuamua unique: astronomers know of no other cosmic object that lets off gas but no dust or ice. Micheli suggested that 'Oumuamua might eject very large dust particles that were invisible to our telescopes.

In November 2018 Shmuel Bialy of the University of Maryland and Avi Loeb of the Center for Astrophysics | Harvard & Smithsonian proposed that the nongravitational force could be caused by sunlight, which exerts a weak pressure on any object placed in its path. To experience enough radiation pressure that we could measure it, however, 'Oumuamua would have to be either extraordinarily thin like a sheet of Mylar (the aluminized plastic used to make birthday balloons) or of very low density. Bialy and Loeb suggested that the object could be a "light sail," a flat, sail-shaped vehicle sent from another civilization and designed to be pushed through space by starlight.

As intriguing as that idea may be, most astronomers favor a natural origin for 'Oumuamua. In February 2019 one of us (Moro-Martín) calculated that for 'Oumuamua to be propelled by sunlight, it would have to be 100 times less dense than air. Such a cos-

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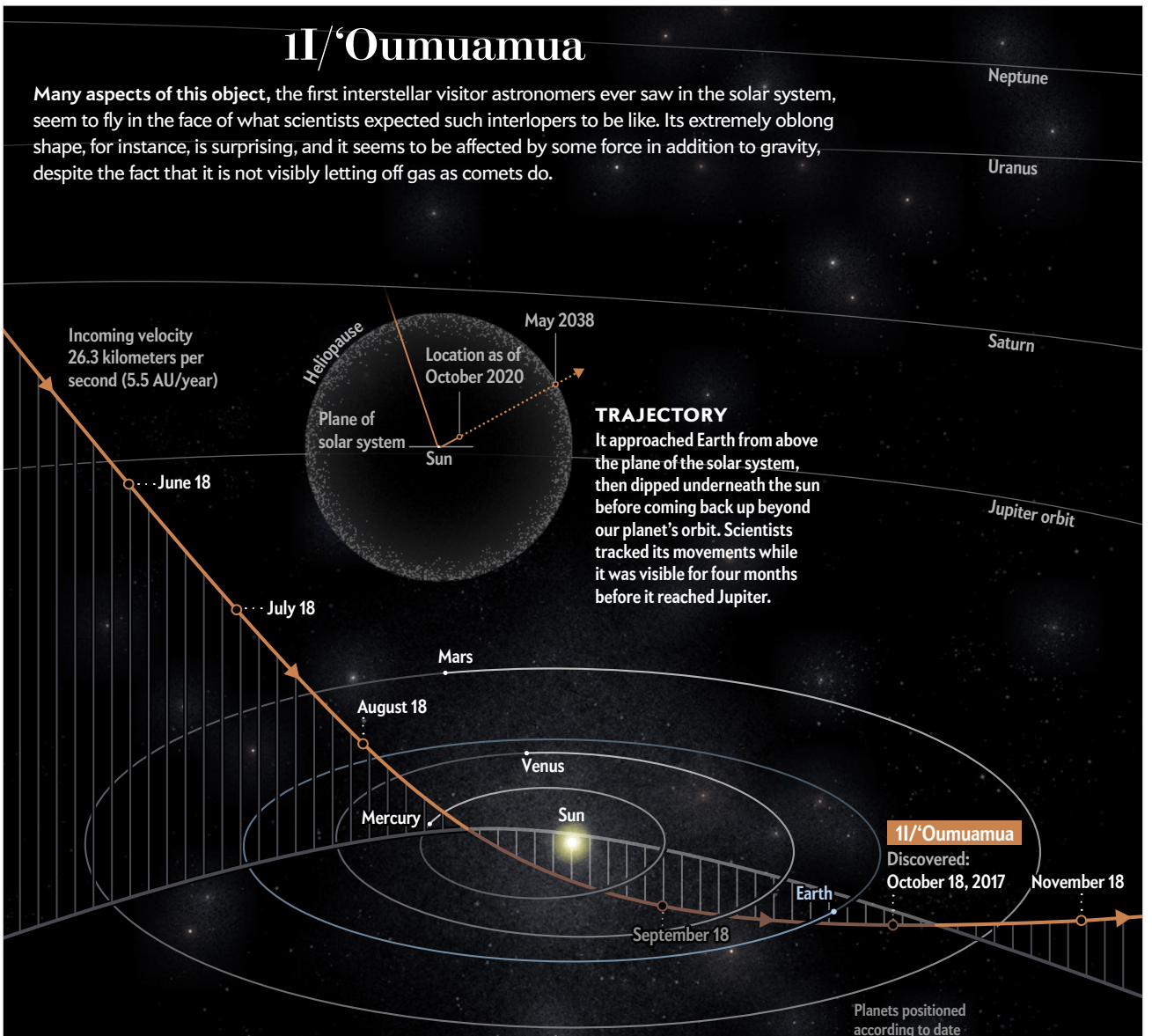
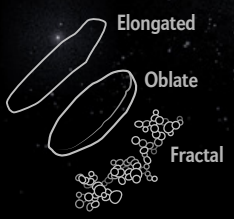
1I/'Oumuamua

Many aspects of this object, the first interstellar visitor astronomers ever saw in the solar system, seem to fly in the face of what scientists expected such interlopers to be like. Its extremely oblong shape, for instance, is surprising, and it seems to be affected by some force in addition to gravity, despite the fact that it is not visibly letting off gas as comets do.

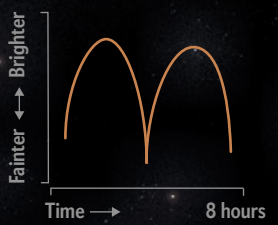


TRAJECTORY
It approached Earth from above the plane of the solar system, then dipped underneath the sun before coming back up beyond our planet's orbit. Scientists tracked its movements while it was visible for four months before it reached Jupiter.

DISCOVERY
It was first spotted by Robert Weryk using the Pan-STARRS 1.6-meter telescope on the Hawaiian island of Maui.



APPEARANCE
Its exact dimensions are unknown, but its highly elongated shape is unlike any of the thousands of solar system bodies that have been measured.



LIGHT CURVE
What astronomers do know of 'Oumuamua's shape comes from its light curve—the variation in light bouncing off it. The extreme changes here show that it must be highly elongated, sometimes presenting a small reflective face and other times a large surface.

ORIGIN
The object is most likely a relic from the formation of a distant planetary system that got ejected long ago.

Source: Small-Body Database Browser, Jet Propulsion Laboratory/NASA (*trajectory*)

Graphic by Matthew Twombly

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mic dust bunny—an "icy fractal aggregate"—might have grown in the outer parts of the protoplanetary disk of another star, where baby planets congeal out of ice and dust rubble. In the summer of 2020 Luu, Eirik Flekkøy and Renaud Toussaint, then all at the University of Oslo, proposed that 'Oumuamua grew from a collection of dust particles in the coma of an active comet, then escaped. This type of material is unknown on Earth but could conceivably survive in the ultimate vacuum of interstellar space.

Given how odd 'Oumuamua is, what might be most incredible of all is that objects like it must be common. We know that this relatively tiny body was detected only because it passed close to Earth and that humans have had the capability to see such an object for only a few years (the Pan-STARRS facility began operating in 2010 but reached full efficiency almost a decade later). Based on statistics alone, these two facts allowed scientists to estimate that the number of similar interstellar interlopers per unit volume of space is about one per 10 cubic AU (one AU, or astronomical unit, is the distance between Earth and the sun). Thus, in the planetary region of our solar system, defined as a sphere with the radius of Neptune's orbit, there must be about 10,000 similar objects, of which 'Oumuamua was only the first one close enough to be detected in the operational lifetime of Pan-STARRS. If these objects take about a decade to cross the planetary region, the average rate of interloper arrivals must be about three a day!

What, then, does this frequency suggest about the origin of 'Oumuamua? Aliens might be capable of sending a Saturn V–size rocket or a large piece of Mylar-like material across the galaxy and through our solar system, but why would they send so many? Even more astonishing, if we extrapolate our analysis from the solar system to the whole of the Milky Way, we find that there must be 1×10^{24} to 1×10^{25} (a trillion trillion to 10 trillion trillion) similar objects in our galaxy. It is hard to believe that an extraterrestrial civilization would have the capacity to flood the galaxy with so much space junk, and it is even more difficult to see why it would do so. Thus, given the maxim that extraordinary claims require extraordinary evidence, most astronomers think 'Oumuamua is just a weirdly shaped, but natural, piece of debris from elsewhere in the galaxy.

A SECOND DISCOVERY

THE SHEER STRANGENESS of 'Oumuamua left astronomers eagerly awaiting the discovery of the second interstellar interloper. Would the next one be as peculiar, or would it look like a regular solar system comet or an asteroid without nongravitational motion?

Without knowing the answers to these questions, we predicted that the second object would arrive within a year or two, based on the estimate that there must be about one body like 'Oumuamua per 10 cubic AU. To our delight, two years after 'Oumuamua, Ukrainian amateur astronomer Gennadiy Borisov discovered C/2019 Q4 using a homemade telescope; it was soon renamed 2I/Borisov—the second interstellar object. It has an orbit even more extreme than that of 'Oumuamua, but it appears to be a rather ordinary comet. Measurements from the Hubble Space Telescope showed that its nucleus is larger than 'Oumuamua, with a radius between 0.2 and 0.5 kilometer. In contrast to 'Oumuamua, 2I/Borisov displays no extreme light curve, and its nongravitational motion is simply a consequence of asymmetric outgassing as ice comes off its surface, just as in solar system comets. In March 2020 it briefly flared in brightness and then took on a doubled appearance as a small piece of the nucleus detached, something commonly observed with solar system comets. In other words, this body is pretty much exactly what we would have expected an interstellar object to be like.

Our expectations are based on theories of planet formation, which suggest a ready mechanism for kicking some objects out of their home planetary systems and into the galaxy, where they may eventually make their way to our little corner of the cosmos. Studies suggest that planet formation begins in an orderly way but ends in a chaotic mess. The sun, for instance, was born 4.6 billion years ago in a flattened, rotating disk that grew as a giant molecular cloud contracted under its own gravity. This disk of gas, ice and dust feeding the nascent star in its center was very dense, which allowed tiny grains to collide and stick to one another. At first pebbles formed, then larger bodies known as planetesimals and, eventually, the planets. Some of the planetesimals escaped further growth and heating when they were scattered to the outer solar system shortly after they formed. There, in deep freeze, they have remained mostly unaltered ever since.

The object's resemblance in size and proportions to a large rocket was hard to ignore.

Sometimes, though, these bodies get scattered back into the inner system, where the sun's heat causes their ice to sublimate; they develop tails of ejected material, and we call them comets. Other planetesimals are expelled from the system entirely, destined to spend eternity drifting among the stars. Once lost in the vastness of the Milky Way, such an object has a negligible chance of reentering the planetary system it came from, but it could certainly be deflected by the gravity of an alien star. Given the chaos of this process and the numerous encounters 'Oumuamua and Borisov must have had before they reached us, we will likely never know precisely how long these objects have been adrift or determine with confidence where they came from.

Nevertheless, we can feel confident that Borisov is an ice-rich planetesimal from the outer regions of the planet-forming disk of an unknown star. In fact, everything we have learned about Borisov—and the proof it offers that some interstellar objects look much like we expected—puts the strangeness of 'Oumuamua in stark relief. Given the extraordinary differences between the two, there is no reason to assume that they share a common origin.

Astronomers are still trying to puzzle out what 'Oumuamua is, and new ideas come up often. One suggestion, proposed in May 2020 by Darryl Seligman of the University of Chicago and Gregory Laughlin of Yale University, is that 'Oumuamua is a novel type of body made of molecular hydrogen ice—a cosmic iceberg that originated in the coldest regions of a molecular cloud. In June 2020, however, Loeb and Thiem Hoang of the Korea Astronomy and Space Science Institute argued that molecular hydrogen is so volatile that such a body could neither have formed in a molecular cloud nor have survived interstellar travel. Another option, put forward in April of that year by Yun Zhang of the National Astronomical Observatories of the Chi-

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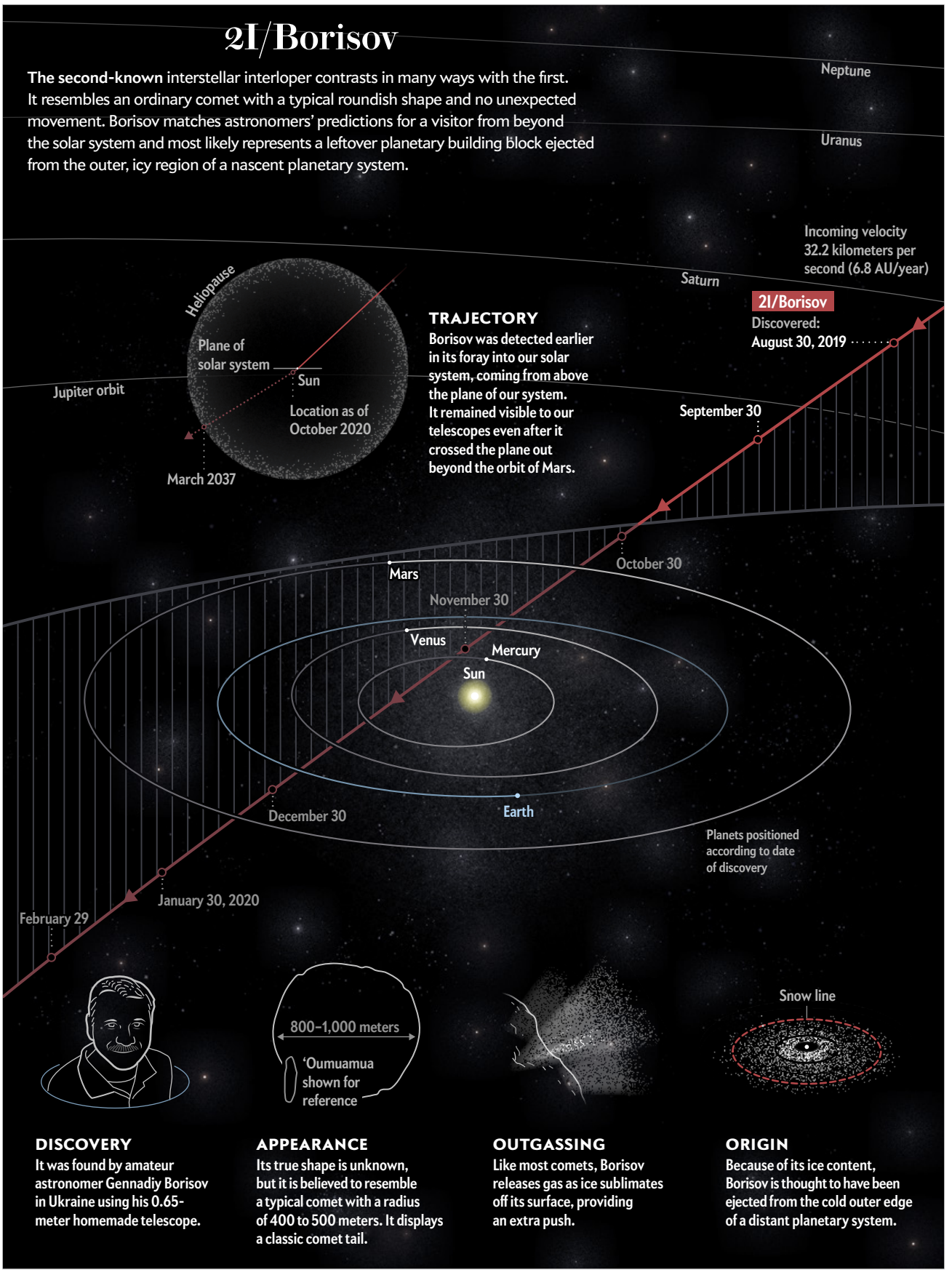
2I/Borisov

The second-known interstellar interloper contrasts in many ways with the first. It resembles an ordinary comet with a typical roundish shape and no unexpected movement. Borisov matches astronomers' predictions for a visitor from beyond the solar system and most likely represents a leftover planetary building block ejected from the outer, icy region of a nascent planetary system.



TRAJECTORY
Borisov was detected earlier in its foray into our solar system, coming from above the plane of our system. It remained visible to our telescopes even after it crossed the plane out beyond the orbit of Mars.

DISCOVERY
It was found by amateur astronomer Gennadiy Borisov in Ukraine using his 0.65-meter homemade telescope.

APPEARANCE
Its true shape is unknown, but it is believed to resemble a typical comet with a radius of 400 to 500 meters. It displays a classic comet tail.

OUTGASSING
Like most comets, Borisov releases gas as ice sublimates off its surface, providing an extra push.

ORIGIN
Because of its ice content, Borisov is thought to have been ejected from the cold outer edge of a distant planetary system.

Source: Small-Body Database Browser, Jet Propulsion Laboratory/NASA (*trajectory*)

Graphic by Matthew Twombly

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nese Academy of Sciences and Douglas N. C. Lin of the University of California, Santa Cruz, is that 'Oumuamua might instead be shrapnel produced by gravitational shredding of a planet or other body passing too near its parent star.

'Oumuamua's strange properties aside, the fact that the object was detected at all runs counter to the conventional wisdom about planetary system formation, which suggests that interstellar visitors should be very rare. We can estimate the number of interstellar planetesimals we expect to exist per unit volume of space based on the observed number of stars and on our knowledge of star and planet formation, stellar evolution and dynamics. The calculation involves many uncertainties, but a generous upper limit is at least a tenth to a hundredth the size of the previously mentioned statistical frequency estimate of 10,000 such objects in the planetary region. Put simply, we cannot account for that much litter in the galaxy. Perhaps as we detect more interlopers and understand them better, the inferred and estimated values of their space density will start to converge. But it is also possible that we are missing an important source of interstellar objects—maybe some process in space other than the planetesimal scattering we have described creates bodies that find their way to us.

LIFEBOATS FROM BEYOND

BESIDES TEACHING US about how planetary systems form, the discovery of interstellar visitors may have a bearing on one of the most fundamental mysteries in science: How did life on Earth begin? One idea, called panspermia, is that the seeds of ancient organisms hitched a ride on asteroids hailing from other systems.

Just as we expect interstellar bodies to enter our solar system occasionally, we must also assume that they sometimes hit our planet. Based on the value of one object per 10 cubic AU that we inferred from the detection of 'Oumuamua and 2I/Borisov, we can estimate that similar objects strike about once every 100 million to 200 million years, thousands of times less frequently than asteroids of comparable size. Most would probably detonate and disperse in the atmosphere, but a few would actually reach the ground. Scientists estimate that over the eons several billion tons of interstellar material must have crashed into Earth.

Could these impacts have delivered life to our planet? The modern scientific notion of panspermia dates back to the 19th century. Surprisingly, asteroids and comets might be good protectors of fragile cellular life. Damaging cosmic rays, capable of breaking DNA, penetrate only a few meters into solid material, so living cells buried inside rocks might survive interstellar journeys lasting millions or even hundreds of millions of years. At near-zero interstellar temperatures, any cells would be in suspended animation. They would need to withstand the shock of planetary impact, but this might not be as problematic as it sounds. Experiments have already shown that earthly bacteria can survive impacts at cosmic speed. Although there is no evidence that life spreads through the galaxy while riding in the bellies of asteroids and comets, given our present state of ignorance, we must acknowledge that this possibility remains.

To improve our understanding of interstellar objects, we need to find more examples. Currently, with only two to go on, our grasp is limited. Fortunately, new developments in astronomy make it very likely that we will soon observe dozens of similar objects, and those discoveries will allow us to better pin down the statistics and to understand their physical properties. Most professional telescopes have very small fields of view, often only a few thousandths of the area of the full moon. But optics and large detectors are now capable of capturing the whole moon and more in a single shot and the entire sky in a night or two of continuous scanning. Powerful computers make it possible to compare successive all-sky scans to find moving objects, including interstellar interlopers.

Having a larger sample of interstellar objects will help us answer many questions about the objects themselves. How many interlopers are strangely iceless and oblong like 'Oumuamua versus akin to a comet like 2I/Borisov? Are there bigger examples? Are there smaller ones? What are they made of? Are some really porous enough to be pushed around by the pressure of light? New data from the Rubin Observatory, now under construction on a Chilean mountaintop, should provide fresh insights. The Rubin telescope has a collecting mirror 8.4 meters in diameter and a three-billion-pixel detector that would have been unthinkable just a decade ago. Each image from this gigantic camera will cover an area 40 times that of the moon, an enormous advance. It will also systematically survey the sky more deeply than has ever been attempted and on a repeated basis. This new facility is expected to reveal interstellar interlopers in abundance, along with vast numbers of asteroids, comets and Kuiper belt objects from our own solar system.

To truly understand the nature of any given interloper, we would like to send a spacecraft to visit it or even land on it. One practical problem is that there is not much time to make plans because these objects move so fast. 'Oumuamua faded to invisibility for even the largest telescopes within months of its discovery. 2I/Borisov was expected to become too faint to detect within a few years. For comparison, space missions often take a decade or more, including their design, approval, construction and launch, making it impossible to plan for any particular interstellar target. A solution might be to send the spacecraft into a storage orbit before knowing where the mission will go. This is the idea behind the European Space Agency's Comet Interceptor, due to be launched in 2029. The Interceptor will park at Earth's L2 Lagrangian point 1.5 million kilometers away, where it can easily maintain a stable orbit as it awaits the flyby of an interesting object. The Interceptor lacks the power to rendezvous with an interloper unless one happens by chance to pass very close to L2, however.

More capable rockets are intrinsically heavy and expensive to launch; even if a flyby is possible, accelerating to hyperbolic orbit speed to grab a sample will not be easy. Spacecraft powered by novel propulsion methods, such as light sails accelerated by a laser beam from Earth or by solar radiation pressure, are another option, but they involve difficulties of their own. Still, the prospect of being able to closely examine an object that unequivocally originated beyond our solar system is extraordinary, and scientists have not been shy in proposing ways to do so. One way or another, we will pry the secrets from our interstellar visitors. SA

David Jewitt is an astronomer at the University of California, Los Angeles, where he studies the primitive bodies of the solar system and beyond.

Amaya Moro-Martín is an astronomer at the Space Telescope Science Institute in Baltimore. She investigates planetary systems and extrasolar comets.

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Radio Signal Mystery

A seeming "alien beacon" from the star Proxima Centauri was a false alarm but a helpful drill for future searches

By Alexandra Witze

A RADIO SIGNAL DETECTED BY AN AUSTRALIAN telescope in 2019, which seemed to be coming from the star closest to the sun, was not from aliens, researchers reported in October 2021 in two papers in *Nature Astronomy*. "It is human-made radio interference from some technology, probably on the surface of Earth," says Sofia Sheikh, an astronomer at the SETI (Search for Extraterrestrial Intelligence) Institute and a co-author of both papers.

But the disturbance, detected by Breakthrough Listen—an ambitious and privately funded $100-million effort—looked intriguing enough at first that it sent astronomers on a nearly yearlong quest to understand its origins. It was the first time that data from Breakthrough Listen triggered a detailed search, and the experience put scientists in a better position to study future candidate detections.

"It's really valuable for us to have these dry runs," says Jason Wright, an astronomer at the Pennsylvania State University. "We need these candidate signals so we can learn how we will deal with them—how to prove they are extraterrestrial or human-made."

MYSTERIOUS BLIPS

SINCE 2016, Breakthrough Listen has used telescopes around the world to listen for possible broadcasts from alien civilizations. The program has picked up millions of radio blips of unknown origin, nearly all of which could be swiftly classified as coming from radio interference on Earth, from sources such as mobile-phone towers or aircraft radar.

The 2019 signal was different. It was detected by the 64-meter Parkes Murriyang radio telescope in southeastern Australia and came from the direction of Proxima Centauri—the nearest star to the sun, just 1.3 parsecs (4.2 light-years) away. Proxima Centauri is of intense interest to SETI researchers, not just because it is nearby. The star has at least two planets, one of which orbits at the right distance for liquid water to be present on its surface—a prerequisite for life as it exists on Earth. A sibling initiative to Breakthrough Listen, known as Breakthrough Starshot, aims to send a tiny spacecraft to this planet in the future to look for life there.

The mysterious signal was first spotted in 2020 by Shane Smith, an undergraduate at Hillsdale College, who was working as a research intern with Breakthrough Listen. Smith was combing through data that Parkes collected over six days in April and May 2019. The telescope had been making observations in the direction of Proxima Centauri for 26 hours. It was not searchng specifically for aliens at the time but was instead monitoring flares on the star's surface, which could hurt the chances for life to arise on nearby planets.

The data included more than four million signals from the vicinity of the star, but Smith noted one signal near 982 megahertz that seemed to originate from the star itself and lasted about five hours. "I was excited to find a signal that matched all the criteria I was looking for, but I immediately remained skeptical of it and thought there had to be some simple explanation," Smith says. "I did not ever think the signal would cause such excitement."

Smith shared the information with his supervisor Danny Price, who posted it on a Breakthrough Listen Slack channel, and the team started investigating in earnest. "My first thought was that it must be interference, which I guess is a healthy attitude, to be skeptical," says Price, an astronomer at the University of California, Berkeley, and the Breakthrough Listen project scientist in Australia. "But after a while I started thinking, this is exactly the kind of signal we're looking for."

The signal, named BLC1 for "Breakthrough Listen candidate 1," was the first to pass all the program's initial screening tests to rule out obvious sources of interference. "It definitely had me wondering 'what if?' for a bit," Sheikh says.

Sheikh, Price and a large group of colleagues began working through possible explanations, from uncatalogued satellites to transmissions from planetary spacecraft. In Australia, the radio-frequency band around 982 megahertz is primarily reserved for aircraft, but the scientists could not identify any airplanes that had been in the area and could account for the signal—and certainly not one present for five hours.

In November 2020 and in January and April 2021, the researchers pointed the Parkes telescope at Proxima Centauri to see whether they could pick up the signal again. They could not.

Eventually the team spotted other signals in the original data that looked a lot like the 982-megahertz signal but were at different frequencies. The team's automat-

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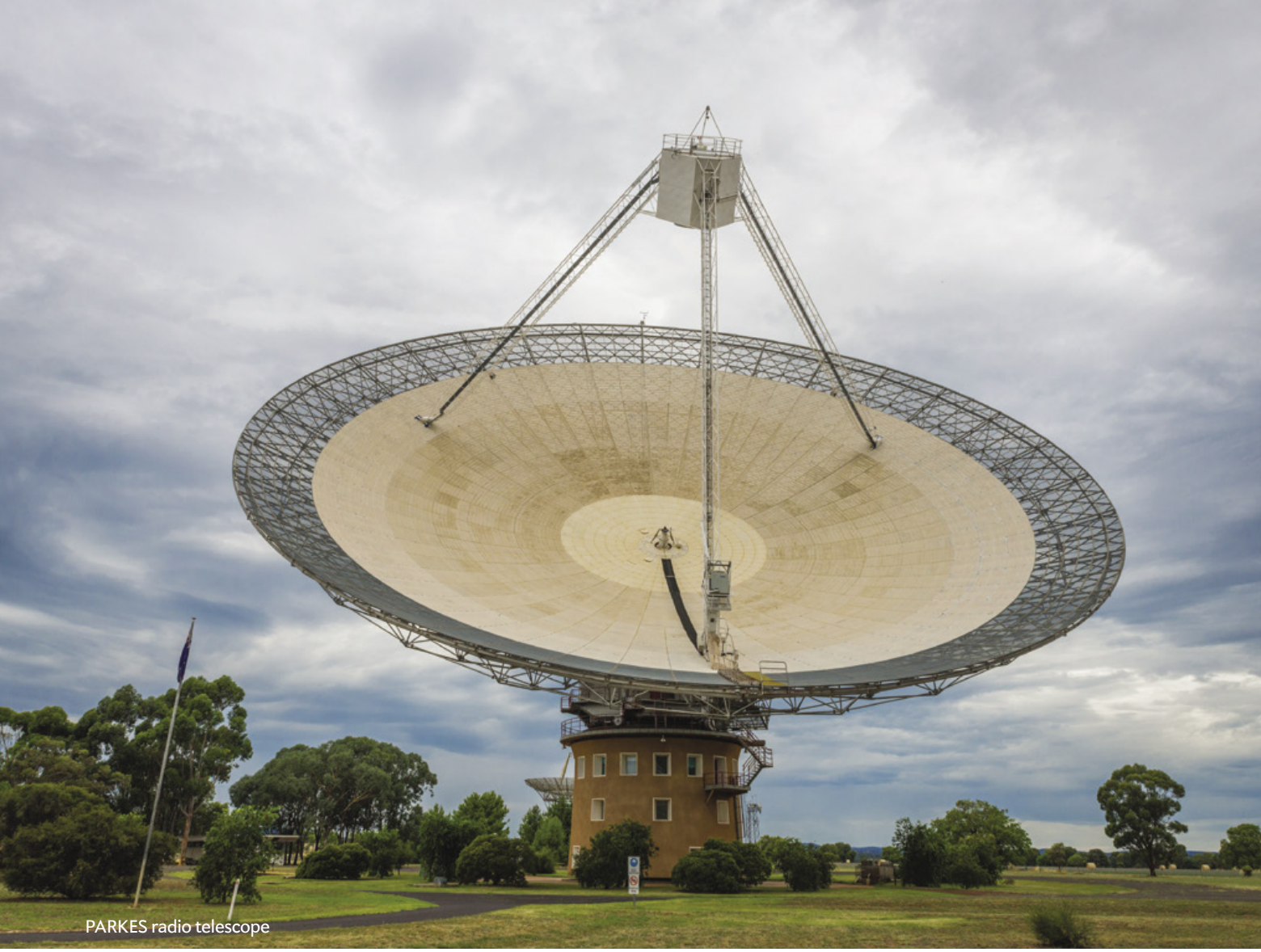

PARKES radio telescope

Getty Images

ed analysis had tossed these signals out as earthly interference. Further analysis showed that BLC1 and these "lookalike" signals were all interference from an unknown source. The signals had modulated and muddied one another, much as a guitar amplifier modulates and distorts a guitar note, which is what made it so difficult to identify BLC1 as interference.

EARTHLY ORIGINS

BECAUSE THE SIGNAL didn't reappear in the 2020 and 2021 observations, it might have been coming from malfunctioning electronic equipment that got shut down or fixed, Sheikh says. The team suspects the equipment was relatively close to Parkes, perhaps within a few hundred kilometers. The frequency of the signal drifts in a way that is consistent with inexpensive crystal oscillators such as those commonly used in computers, phones and radios, says Dan Werthimer, a SETI astronomer at U.C. Berkeley who specializes in signal processing.

Working with another student, Sheikh is now using machine-learning algorithms to tease out what frequency the interfering equipment was transmitting at, which might help them track down its source. One lingering mystery is why the signal seemed to appear only when the telescope was pointed at Proxima Centauri. That might just be an unfortunate coincidence if the cadence of the interference mimicked the cadence with which the telescope was looking at the star.

Radio interference has bedeviled other astronomical searches before, such as when flickering signals picked up at Parkes turned out to be the result of people microwaving their lunches. The famous "Wow!" signal, detected in 1977 by a radio telescope in Ohio, was a powerful blip so intriguing that the observing scientist scribbled "Wow!" in the margins of the computer printout—but its origin could never be traced.

Alien searches have become much more sophisticated since then, Sheikh notes. "Many groups assumed that if you had a detection that only showed up when you were pointed at the source, that was it, break out the champagne, you're done," she says. "As technology changes, the way we vet signals also has to change—and that hadn't come together until BLC1." One of the *Nature Astronomy* papers features a detailed checklist to help astronomers determine whether their signal is truly from aliens.

"The universe gives us a haystack," says Ravi Kopparapu, a planetary scientist at the NASA Goddard Space Flight Center. "It is our need to find the needle in it and make sure that it is actually a needle that we found." SA

Alexandra Witze works for *Nature* magazine.

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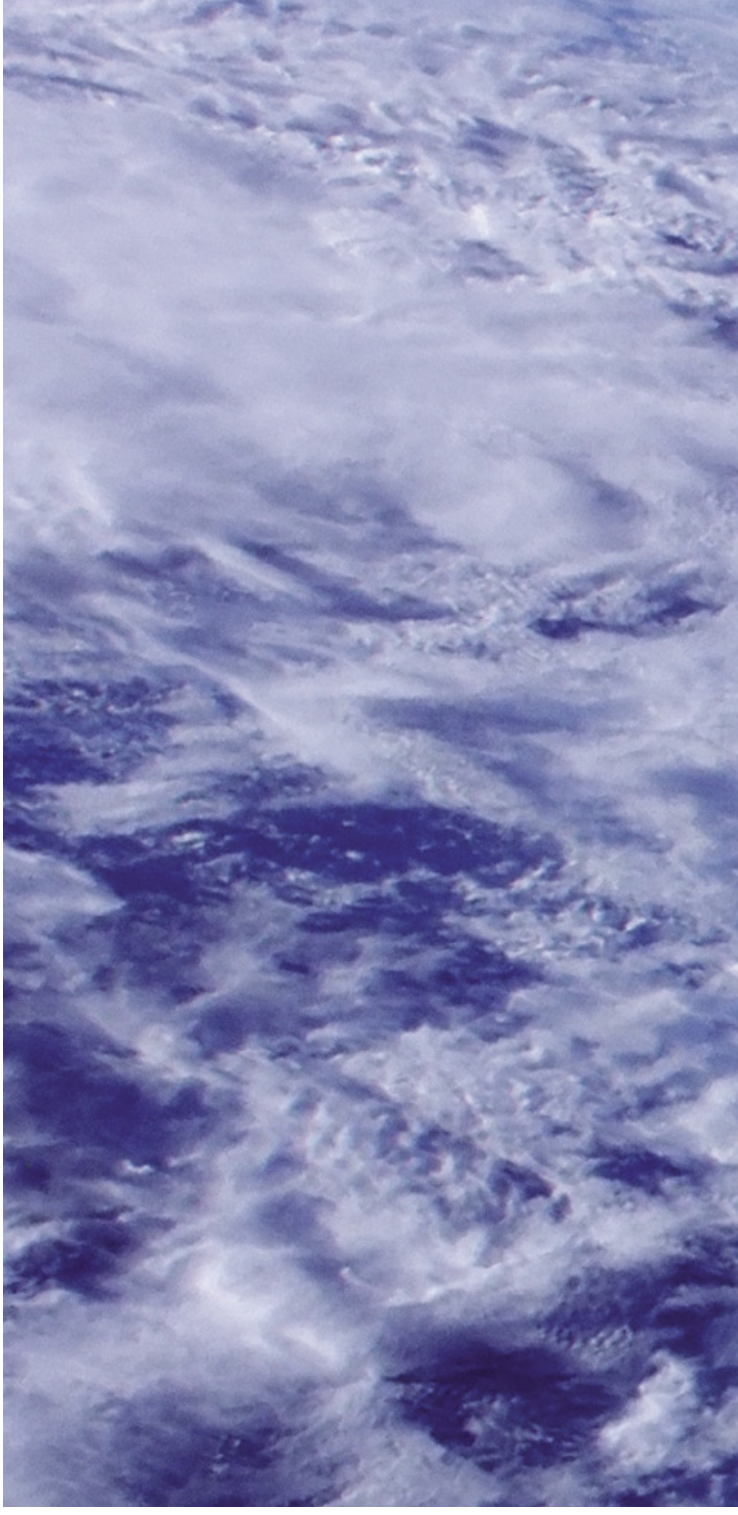
OPINION

Meteors beyond the Solar System

A high-speed fireball that struck Earth in 2014 looked to be interstellar in origin, but verifying this extraordinary claim required extraordinary cooperation from secretive defense programs

By Amir Siraj



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On January 8, 2014, at 17:05:34 UT, a meter-sized rock from space streaked through the sky off the coast of Manus Island, Papua New Guinea, burning up with an energy equivalent to about 110 metric tons of TNT and raining debris into the depths of the Pacific Ocean. Similar-sized fireballs are not uncommon occurrences in Earth's skies; in fact, a few dozen of them occur every year. But what was notable about this particular meteor was the very high speed and unusual direction at which it encountered our planet, which collectively suggested it came from interstellar space.

Sensors on a classified U.S. government satellite designed to detect foreign missile launches were the sole known witnesses to the fireball. Thanks to a partnership between the Department of Defense and NASA, the data describing the event eventually were shared on a public database hosted by the Center for Near Earth Object Studies (CNEOS) within the space agency's Jet Propulsion Laboratory, along with data for more than 900 other fireballs recorded by U.S. government sensors between 1988 and the present day. The data for these events include dates, times, latitudes, longitudes, altitudes, speeds, three-dimensional velocity components and energies for each. Notably omitted from the database are the uncertainties for most of these measurements—presumably to ensure the precision thresholds for U.S. global sensing capabilities are not divulged, as this information could potentially be exploited by adversaries.

My involvement with this meteor traces back to April 2019, when my academic adviser at Harvard University, astrophysicist Avi Loeb, brought the CNEOS fireballs catalog to my attention. At the time, he and I were about eight months into our studies of data related to 'Oumuamua, the object identified in October 2017

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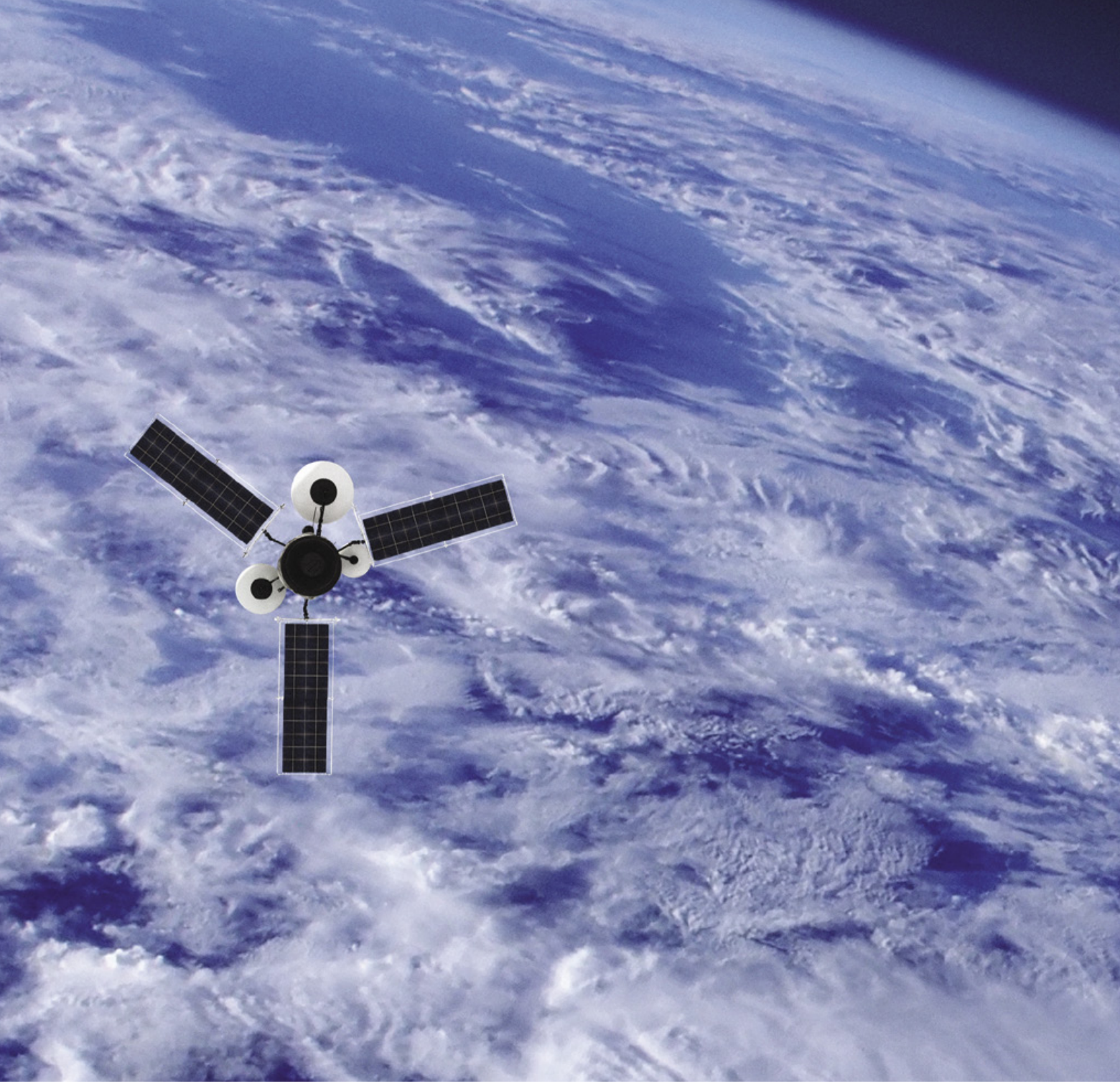

SPY SATELLITES confirmed our discovery of the first meteor from beyond the solar system.

as the first-known interstellar visitor to the solar system. Because ‘Oumuamua originated from outside the solar system, each of its properties, including its very detection, conveyed previously inaccessible information about our cosmic neighborhood. With the wealth of knowledge carried by interstellar visitors foremost in our minds, Loeb and I had been pondering the possibility of finding others to study, and the CNEOS data seemed promising. Within days I had identified the 2014 Manus Island fireball as a potential interstellar meteor candidate. Loeb then suggested that I use the speed of impact combined with knowledge of the kinematics of small-body populations in the solar system to estimate the probability that it originated from elsewhere, beyond our solar system. Contemplating this approach, I proposed a more precise method to derive the object's trajectory that accounted for the gravitational influences of our sun and its planets. Loeb agreed with my proposal, and I swiftly got to work.

At Earth's distance from the sun, any object moving faster than about 42 kilometers per second is in an unbounded, hyperbolic orbit relative to our star, meaning that it is too speedy to be captured by the

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sun's gravity. Anything traveling faster than this local celestial speed limit, then, may come from (and if unimpeded should return to) interstellar space. The CNEOS entry for the 2014 Manus Island fireball indicated the meteor hit Earth's atmosphere at about 45 kilometers per second—very promising. Some of this speed, however, came from the object's motion relative to Earth and its motion around the sun. Teasing apart these effects with the help of computer programs that I wrote, I found that the object had overtaken Earth from behind before striking our atmosphere, and it probably had a sun-relative speed closer to 60 kilometers per second. The corresponding orbit that I calculated was clearly unbound from the sun—even if there had been large uncertainty errors. If the data were correct, this event would be the first interstellar meteor ever discovered. And it was hiding in plain sight.

Extraordinary claims, of course, require extraordinary evidence. So Loeb and I reverse engineered estimates of the classified satellites' measurement errors, using independently verified data on other fireballs in the CNEOS database and elsewhere in the scientific literature. After this arduous reality check, we were left with the same astonishing conclusion: the 2014 fireball had clearly originated from interstellar space. In short order, we drafted a paper reporting our discovery for peer-reviewed publication.

The holy grail of interstellar object studies would be to obtain a physical sample that originated from outside the solar system.

Journal referees balked at the unknown nature of the error bars, so we enlisted the help of Alan Hurd and Matt Heavner, scientists at Los Alamos National Laboratory with high-level security clearances and an interest in promoting collaboration with the public sector to enable blue-sky science. Heavner made contact with the anonymous analyst who had derived the meteor's velocity components from the classified satellite observations and who confirmed that the relevant uncertainties for each value were no higher than 10 percent. Plugged into our error analysis, this implied an interstellar origin with 99.999 percent certainty, but the paper was again turned down by referees, who raised objections about the fact that the statement about uncertainties was from a private communication with an anonymous U.S. government employee and not an official statement from the U.S. government, which Heavner had difficulty in procuring. After several further failed attempts to pierce the veil of secrecy to the satisfaction of journal reviewers, we regretfully moved on to other research, leaving the true nature of the 2014 meteor unconfirmed.

A year later, however, we were approached by Pete Worden, the chair of the Breakthrough Prize Foundation, with an introduction to Matt Daniels, who at the time was working for the Office of the Secretary of Defense. Daniels had read our preprint paper about the 2014 meteor and wished to help us confirm its origin from within the U.S. government. After a year of laboriously navigating multiple layers of government bureaucracy, in March/April 2022 Daniels was able to procure official confirmation from Lieutenant General John Shaw, deputy commander of U.S. Space Force, and Joel Mozer, chief scientist of the branch's Space Operations Command, of the relevant uncertainties—and thus effective confirmation that the meteor was of true interstellar origin.

Three years after our original discovery, the first object originating from outside the solar system observed to strike Earth—the first known interstellar meteor—was officially recognized. The 2014 meteor is also the earliest recorded interstellar object to be detected in the solar system, predating 'Oumuamua by over three years, and is one of three interstellar objects confirmed to date, alongside 'Oumuamua and the interstellar comet Borisov.

The 2014 object's interstellar nature carries fascinating consequences. Its size implies that each star needs to contribute a significant mass of similar objects over its lifetime to make the 2014 detection likely—suggesting there are many more interstellar meteors to be found. And its high speed relative to the average speeds of our neighboring stars suggests that it could have been ejected from deep within another planetary system, relatively close to its star. This is surprising, as one would naively expect most interstellar objects to instead originate from far more distant circumstellar regions where escape velocities are lower, namely, the clouds of comets that exist at the outskirts of many star systems.

This new field, the study of interstellar meteors, certainly has much to tell us about our place in the cosmos. Further investigations of the observed properties of the 2014 meteor could reveal new insights about our local interstellar environment, especially when compared with the characteristics of its successors, 'Oumuamua and Borisov. Meteor databases are ripe for follow-on searches, and fresh motivations exist for building new sensing networks, with a focus on detecting future interstellar meteors. Observing an interstellar meteor burn up in real time would allow for the study of its composition, potentially yielding novel insights into the chemistry of other planetary systems.

The holy grail of interstellar object studies would be to obtain a physical sample of an object that originated from outside the solar system—a goal as audacious as it is scientifically groundbreaking. We are currently investigating whether a mission to the bottom of the Pacific Ocean off the coast of Manus Island, in the hopes of finding fragments of the 2014 meteor, could be fruitful or even possible. Any sufficiently large interstellar meteor discovered in the future should also produce a shower of debris, which scientists could potentially track down and analyze. There is, of course, another approach for getting samples, which, as director of interstellar object studies for the Galileo Project, I am excited to also be pursuing: a spacecraft rendezvous. In collaboration with Alan Stern, the principal investigator of NASA's New Horizons mission, we have received funding to develop a concept for a space mission to some future interstellar object.

Like exotic seashells, these messengers from the stars have been washing ashore on our planetary beach for billions of years, each carrying secrets of their—and our—cosmic origins. Now, at last, we are starting to comb the shoreline. SA

Amir Siraj is an undergraduate in the Harvard University–New England Conservatory of Music dual degree program studying astrophysics and piano performance. He is the youngest laureate of the 2021 Forbes 30 Under 30 science list.

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Breakthrough Communications

Sparked by major advances in their field, astrobiologists are grappling with how best to tell the world if they find alien life

By Jonathan O'Callaghan

Relatively soon, some prominent astrobiologists say, we will most likely have either found compelling evidence for extraterrestrial life or banished its possible existence to the ever shrinking edges of the cosmos beyond the rapidly expanding reach of our observations. Such answers could come by the end of the 2030s from any of a number of initiatives ardently seeking alien life. By then, samples from Mars will have arrived back on Earth, perhaps containing concrete proof that the Red Planet once harbored organisms or still does today. Spacecraft at Jupiter's Europa and Saturn's Titan will be scouring both moons for signs of life residing in each world's subsurface ocean or, in the case of Titan, on the surface itself. And advanced telescopes on the ground and in space should be probing the atmospheres of potentially habitable exoplanets around nearby stars, looking for any that share the same biology-infused cocktail of gases as our own living Earth.

As confident as astrobiologists may be that their quest will soon bear fruit, however, they are far less certain of how to communicate that success if and when it occurs. How should they go about informing the world that we are truly not alone in this universe—especially given their field's long, troubled history of dubious claims and false alarms? They have been fooled before, after all.

In an October 2021 article published in *Nature,* a group of scientists came to grips with the problem. Led by NASA's chief scientist James Green, the researchers proposed a new framework to help verify and then communicate the detection of biosignatures beyond Earth, like the Torino scale for assessing the danger of asteroids. Their idea is to use a scale, from level 1 to level 7, that will allow confidence in any given case to be gradually increased. Known as the "confidence of life detection," or CoLD, scale, it calls initially for simple confirmation that a result is not linked to contamination or some obviously abiotic origin, whereas its final levels would represent robust follow-up observations solidifying a link to life. "These things are complex," Green says. "But we really need to be able to communicate it simply."

There is no shortage of cautionary tales from previous efforts to publicize apparent breakthroughs. In 1996 President Bill Clinton heralded the discovery of a meteorite from Mars, ALH84001, that appeared to contain signs of life. "If this discovery is confirmed, it will surely be one of the most stunning insights into our universe that science has ever uncovered," he said in a speech at the White House. The finding was not confirmed: later analysis poured cold water on the tentative evidence of Martian life. Luckily, astrobiology's positive public perception emerged relatively unscathed. Yet a repeat of that incident could now have disastrous consequences. "Today we have social media, so rumors, innuendo and purposely false information propagate like wildfire," says former NASA chief historian Steven Dick. "[It's] all the more reason to communicate effectively."

More recently, the supposed detection on Venus of atmospheric phosphine, a possible biosignature gas, had many suggesting a biological origin, but that detection has itself since been called into question. More outlandish ideas, such as the suggestion that the interstellar object 'Oumuamua found in our solar system in 2017 may have been an alien spacecraft rather than an asteroid or comet, have been met with widespread disdain from scientists and have the potential to dampen confidence in genuine detections of life. The CoLD scale could prevent scientists from "crying wolf" in this manner, Green says, because any overly cavalier claims would not pass the more stringent tests required to progress up the scale. "Life-detection measurements can be sensationalized," he says.

Deciding how to approach actual detections of biosignatures is a topic other scientists have been considering, too. In July 2021 scientists met virtually at the Standards of Evidence for Life Detection workshop, led by NASA's Network for Life Detection (NfoLD) and Nexus for Exoplanet System Science (NExSS), to discuss the idea of establishing a framework much like CoLD. Hundreds of scientists took part, with many in favor of more rigorous communications protocols. "The potential for us to actually have some sort of interesting life-detection event

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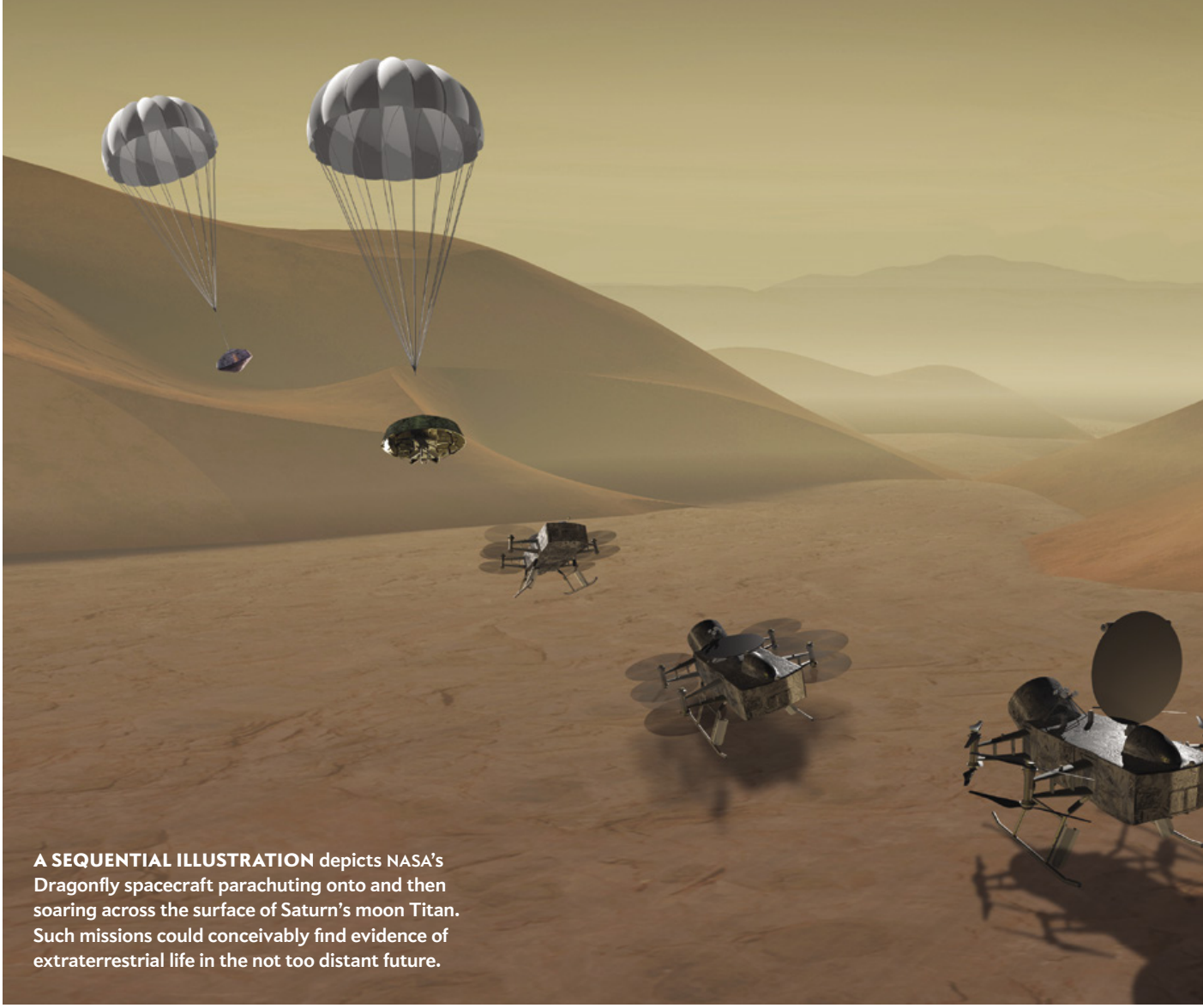

A SEQUENTIAL ILLUSTRATION depicts NASA's Dragonfly spacecraft parachuting onto and then soaring across the surface of Saturn's moon Titan. Such missions could conceivably find evidence of extraterrestrial life in the not too distant future.

NASA

on another world is becoming greater," says the workshop's co-chair Heather Graham of the NASA Goddard Space Flight Center. "We want to get ahead of that."

If scientists were to adopt the CoLD scale, the first of its seven steps, or levels, would be the actual detection of a potential biosignature. Next, scientists would need to rule out contamination before demonstrating how the signal could be biological in origin. Nonbiological sources would then need to be ruled out, followed by an independent additional detection of a similar biosignature. Further observations would need to rule out nonbiological ideas before, finally, follow-up observations showed other examples of biological activity in the same environment, making a detection a level 7—essentially, proof of alien life.

Part of the hope is that the scientific community at large would agree to use such a scale. Agencies such as NASA might also agree to do so, which would also help dictate future missions. "If we're stuck at level 4, and we think we can go to level 6 with a mission, I want to fund that," Green says. Ultimately, once use of a scale such as CoLD became ubiquitous, reviewers of journal papers could require authors to include it in any claim of biosignature detection. "One of the things we discussed at the workshop was: How do we incentivize people to use this?" says Victoria Meadows of the University of Washington, who was the workshop's other co-chair. "The bottom line is that if we don't have such a scale, then people won't use it."

The call for such a step-based approach is driven by the unescapable likelihood that any initial detection of alien life is likely to be ambiguous rather than a smoking gun: any glaringly obvious indication of alien life would have been clear by now, decades into the hunt. So more subtle searches based on circumstantial evidence are coming to the fore. In October 2021, for example, Zoë Havlena, a Ph.D. student at the New Mexico Institute of Mining and Technology, was part of a NASA-funded team that traveled to cave walls in Italy's Apennine Mountains to collect and study samples of a mineral called gypsum, which is sometimes associated with biological activity and may be present on Mars. "[Gypsum on Mars] may be similar to what we're seeing in these cave systems," Havlena says.

Elsewhere on Mars, NASA's Perseverance rover is collecting rocky samples to return to Earth in the early 2030s that may contain evidence of life. Its first cache, however, was actually a sniff of the Martian atmosphere, Green says, to tease out whether the thin air around the rover contained methane. Previous missions—as well as telescopes on Earth—have found evidence for occasional bursts of the gas suffusing Mars's atmosphere. On our planet, methane is replenished by biological activity,

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and Perseverance's samples could reveal such activity if the same is true on Mars. Currently on the CoLD scale, methane on Mars would rank at "about a [level] 4," Green says. But if Perseverance's sample is found to contain not only methane but methane rich in an isotope called carbon 12, that could change. "Life loves carbon 12," Green says. "If all the methane in this tube is carbon 12, we just increased our CoLD level by one." The next step would be to fly across the surface—with a drone like Perseverance's Ingenuity but bigger—to localize the methane to a source that could be directly investigated.

Outside of Mars, both Europa and Titan are promising locations to look for life because of their extensive subsurface oceans and, in the case of the latter, a thick atmosphere and lakes of liquid hydrocarbons. But any evidence found at the two moons is also likely to require careful analysis. Europa will be studied by NASA's Europa Clipper mission from 2030 and the European Space Agency's (ESA's) Jupiter Icy Moons Explorer (JUICE) mission in 2031, while Titan will play host to a robotic drone—NASA's Dragonfly—by the mid-2030s. Madeline Garner, a graduate student at Montana State University, is currently investigating whether an instrument could be designed for robotic spaceflight that could identify the existence of DNA and RNA on these and other alien worlds. "Currently there's no known abiotic source" for DNA and RNA, Garner says. Her research into solid-state nanopore technology, now in use on the International Space Station to sequence DNA, could provide a conclusive detection capability for space probes. "If we find DNA or RNA, we know that's life," she says.

Beyond our solar system, scientists are preparing for a new era of exoplanet studies that could reveal tentative evidence for life on other worlds. At ESA, work is afoot on the Planetary Transits and Oscillations of Stars (PLATO) mission—set to launch in 2026—which will seek to find elusive Earth-like worlds orbiting sunlike stars. "We don't have a clear detection of a rocky planet in the so-called habitable zone of a solarlike star," says Heike Rauer, head of the Institute of Planetary Research at the German Aerospace Center. PLATO will aim to address that. "The best case will be a real Earth twin: a planet like Earth's mass and size the same distance from a star like our sun," Rauer says.

If or when such worlds are found, sophisticated orbital observatories now being discussed—beyond the realm of NASA's James Webb Space Telescope, which launched in December 2021—could lavish them with deeper scrutiny. Such telescopes could include a multibillion-dollar project being considered by NASA, perhaps launching in the 2040s, that could directly image Earth-like planets around sunlike stars, crudely sniffing their atmospheres for signs of habitability and life and even mapping their surfaces. "We could see when the oceans are underneath us versus the continents and potentially a forest signature on the land surfaces," says Shawn Domagal-Goldman, supervisor of the Planetary Environments Laboratory at the NASA Goddard Space Flight Center. If some verdant aqueous world also displayed biosignature gases such as oxygen and methane, many scientists would be convinced their long search for life had been successful. "It would be very difficult to observe a planet with the composition of Earth's atmosphere and figure out ways for nonlife processes to produce that," says Giada Arney, an exoplanet scientist at Goddard.

A framework like CoLD could go a long way toward helping anyone, from researchers to journalists to the general public, assess how excited to be about such detections. But not everyone is convinced by the idea. Caleb Scharf, director of astrobiology at Columbia University, doubts that scientists could control the narrative and is uncertain the public would comprehend the carefully constructed messaging. "I question whether or not the scientific community is really in control of that," he says. "Just look at the past couple of years with COVID, where time and time again, we've been presented with statistics and probabilities, and we're all horrible at interpreting that stuff."

What is certain, though, is that things are progressing apace. "We're in a very different situation than even 10 years ago," Scharf says. Research across a range of fields, from examining caves on Earth to visiting distant worlds, is on the cusp of bringing us closer to the discovery (or continued refutation) of alien life than ever before. Deciding how to communicate such a thing to the world, whether through a framework like the CoLD scale or otherwise, is something that may well be worth discussing sooner rather than later. "It feels like we're not alone," says Graham Lau, an astrobiologist at the Blue Marble Space Institute of Science in Seattle. "If there is life out there, we must be close right now." SA

Jonathan O'Callaghan is a freelance journalist covering commercial spaceflight, space exploration and astrophysics.

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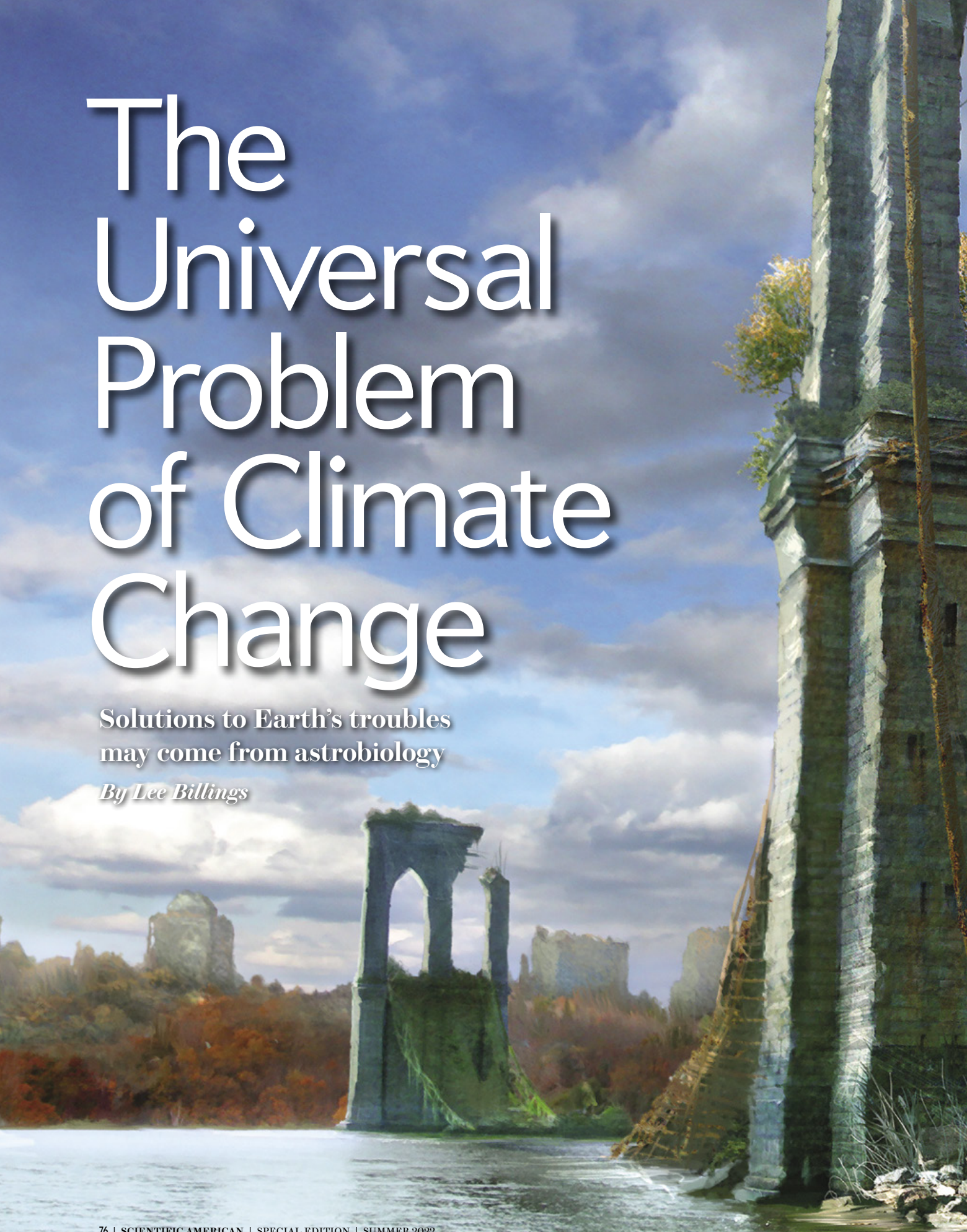
The Universal Problem of Climate Change



Solutions to Earth's troubles may come from astrobiology

By Lee Billings

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DARK FUTURES may lie ahead. Results from modeling the co-evolution of technological civilizations and their planetary climates suggest that aliens could, much like human societies in Earth's recent history, suffer self-inflicted collapses caused by rapid environmental degradation.

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Much has been written about the Anthropocene—a proposed new division of geologic time in which humans are a dominant force for planetary change: When did it begin? How might it unfold? And can we, the supposed masters of Earth, actually use our powers to make our planet a better place?

Understandably, most of the Anthropocene's literature to date both in the popular press and in peer-reviewed publications has been decidedly Earth-centric. Yet in a series of papers and his 2018 book *Light of the Stars: Alien Worlds and the Fate of the Earth,* astrophysicist Adam Frank argues that the Anthropocene's origins and implications are best understood in the context of astrobiology, the study of life in the universe. Climate change and other environmental effects associated with humankind's global ascendancy, he says, most likely are universal phenomena for any and every technological civilization that emerges somewhere in the cosmos. Which means the most crucial insights governing the Anthropocene may come less from studying the ground beneath our feet and more from turning our gaze to the heavens.

Scientific American spoke with Frank, a professor at the University of Rochester, about the lessons to be learned from speculations about alien civilizations battling climate change. [*An edited transcript of the interview follows.*]

What motivated you to write this book?

The book was inspired by some frightening conversations I ended up having with climate change denialists in response to my pieces on that topic for National Public Radio and the *New York Times*. It was terrifying, really, to see how locked into their perspective these people are and to realize there's this false narrative about climate change, which we're stuck in. So this was motivated, in part, by my thinking about how to change the discussion.

Over the years what I've come to understand is that human-driven climate change is really an astrobiology problem. It's not a problem of politics. It's not a problem of businessmen versus environmentalists. We are talking about something much bigger—a planetary transition, which some scientists label as the Anthropocene. Climate change is just one aspect of this new human-dominated period. My argument is that Anthropocenes may be generic from an astrobiological perspective: what we're experiencing now may be the sort of transition that everybody goes through, throughout the universe. And there are probably some common features to long-lived civilizations and the planets they inhabit.

I really started exploring this in 2014, when I co-authored a paper with Woody Sullivan of the University of Washington that proposed using dynamical systems theory to model some of these planetary transitions. We argued that it's possible to identify the basic paths that "exocivilizations" might follow and the feedbacks that might occur when they begin altering their planetary climates. In a follow-up paper that I published with several colleagues, we went ahead and actually did some of that modeling.

Why would you have any faith in models examining the behaviors of exocivilizations—something no one has ever seen?

I like to draw a parallel to the Higgs boson. This is a fundamental particle that was "discovered" in 2012, but really you could say it was discovered in 1964. That was when three papers appeared extrapolating from well-understood physics to propose this particle that would wait nearly half a century before actually being seen. The details obviously would have to be filled in by actual data, but in that intervening time physicists went quite far in thoroughly extrapolating the particle's nature.

Thus, when it comes to thinking about the interactions between an advanced technological civilization and its planet, well, we actually know a lot more about that today than people knew about the Higgs boson 50 years ago. We have lots of examples of planetary climates that we've studied right here in the solar system—Venus, Mars, Titan, Jupiter, and so on. And we've got computer models that can nicely forecast, for instance, the weather on Mars! So we really do understand climate pretty well. And a civilization, to some degree, is just a mechanism for transforming energy on a planetary surface. This gets us into the realm of thermodynamics on global scales, which is supercool.

As long as we ask the right sort of question—"What is a planet's response to having this energy dumped into it?"—we have reasonably good "guardrails" that allow us to address it.

But that's mostly planetary science. What about the social or biological aspects here? How are you modeling that?

Well, just as we understand planetary climates pretty well, we can use the basic, fundamental tenets of life to guide us, too. Organisms are born, some of them reproduce, and they die. Living things consume energy, and they excrete waste. That should be true even if they're made of silicon or whatever.

The next step is to incorporate principles of population biology, in which the idea of "carrying capacity"—the number of organisms that can be sustainably supported by the local environment—is very important. This approach can also be mathematically applied to the state of a planet. So in our modeling work we've got an equation for how the planet is changing and an equation for how the population is changing. What ties them together is the predictable result that as environmental conditions on a planet get worse, the total carrying capacity goes down. A civilization with a population of n will use the resources of its planet to increase n, but at the same time, by using those resources, it tends to degrade the planet's environment.

In our study, we used these basic ideas to address the question of if, and how, exocivilizations can get through their own versions of the Anthropocene. Our first models were pretty simple but gave us a pretty rich view of the possible trajectories for exocivilizations.

What were the results of your modeling? And do they make you feel optimistic or pessimistic about our own prospects?

In the models, we saw three classes of behaviors, three trajectories: A "die-off," where the population overshoots the carrying capacity and then dwindles; a "steady state," where the population growth slows and ends up within the bounds of carrying capacity; and a "collapse," where the population and the carrying capacity both just drop like a stone.

It's important to remember we aren't trying to say any particular history is

Kenn Brown and Chris Wren *Mondolithic Studios (preceding pages)*

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bound to play out on any particular planet. We are looking at the average properties of "successful" versus "unsuccessful" trajectories for civilizations reaching this Anthropocene-like planetary transition.

The results actually made me feel both optimistic and pessimistic. I was happy to see we did find sustainable steady states—it could've turned out that they didn't exist. So our models predicted that long-term civilization/planet co-evolution is possible. Hooray!

But we also found trajectories where equilibrium could be reached only after 90 percent of your population died off. It's not even clear that a complex technological civilization could survive losing nine out of every 10 individuals. It might well just descend into chaos.

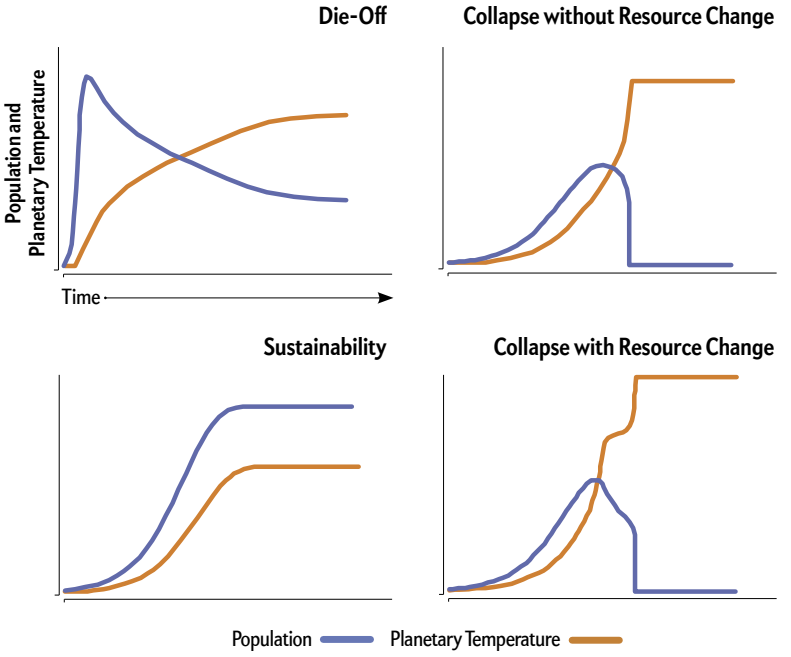
And there was also a fourth and really chilling trajectory we found. It popped up when we looked at how a civilization might switch from high- to low-impact energy sources—such as switching from fossil fuels to solar power, for instance. In some of those scenarios, where the population is soaring and the planet is heating up, the civilization shifts to the low-impact energy resource, and everything seems to get better at first—but then a collapse occurs anyway. This fourth trajectory is really scary because it suggests you can make all the right choices and still have things not work out.

Why would that happen?

Because planets are complex systems that exhibit nonlinear dynamics. Messing around with a planet's climate can be like rolling a big rock down a hill. Once the rock really gets going, there's no turning back, and maybe it just shoots right off a cliff.

The climate is basically a giant planet-sized machine with lots of moving parts—the atmosphere, the lithosphere, the cryosphere, the biosphere—and the interactions among those moving parts may be quite sensitive. So if you push it hard enough, even if you stop pushing it shortly after, there isn't always a way to recover. That's one of the big messages of the book. We have to start thinking like a planet. Our view of climate change—the faux political debate—is so narrow because we think we're the first time this has ever happened. We're kind of like cosmic teenagers who are stuck in our own immaturity.

FOUR SCENARIOS for the fate of technological civilizations and their planets, based on mathematical models, were developed by Adam Frank and his collaborators. The blue line plots the trajectory of the civilization's population; the orange line shows the co-evolving trajectory of the planet's temperature (a proxy for climate).



So where do you think Earth is in this spectrum of possibilities?

I don't think anyone knows yet. More work needs to be done—better models with more realistic climates. There has certainly been a lot of discussion in the earth science literature about planetary "tipping points," the idea that you push too far and, whoops, now you're tipped over to another state. Clearly, people worry about this. But it's unclear as to where and what exactly the tipping points are and where we may be relative to them.

But back to the idea of "changing the discussion"—your motivation for writing the book. Surely we could do more with these ideas than just discuss them. Don't they recommend some action?

Of course, they do—but most of those actions are indistinguishable from ones that follow from lots of other work in climate science and policy.

I really do think, though, that the route to our making it through the Anthropocene runs through other planets. We aren't going to become a sustainable planetary civilization by only dealing with Earth. I give lots of examples in the book, but one of the best is the fact that the climate models that revealed the possibility of "nuclear winter"—a global cooling caused by the atmospheric effects of a nuclear war—relied heavily on data about Martian dust storms. Talk about cross-fertilization! Those nuclear winter models totally changed the debate about nuclear weapons, and they came from understanding another world.

So we can't just sit here studying tipping points on Earth at the expense of going out and exploring other worlds and looking for life and intelligence elsewhere, because the knowledge we gain from that is probably essential for our own future. Think of it this way: If you're sick and go to the doctor to be cured, the doctor will have pretty limited abilities if he has only ever studied [just] you. If he has studied you and lots of other people, [however,] he'll have a much clearer picture of what ails you. It's probably like that with planets and civilizations, too. SA

Lee Billings is a senior editor for space and physics at *Scientific American*.

Source: "The Anthropocene Generalized: Evolution of Exo-Civilizations and Their Planetary Feedback," by A. Frank, J. Carroll-Nellenback, M. Alberti and A. Kleidon, in *Astrobiology*, Vol. 18, No. 5; May 2018

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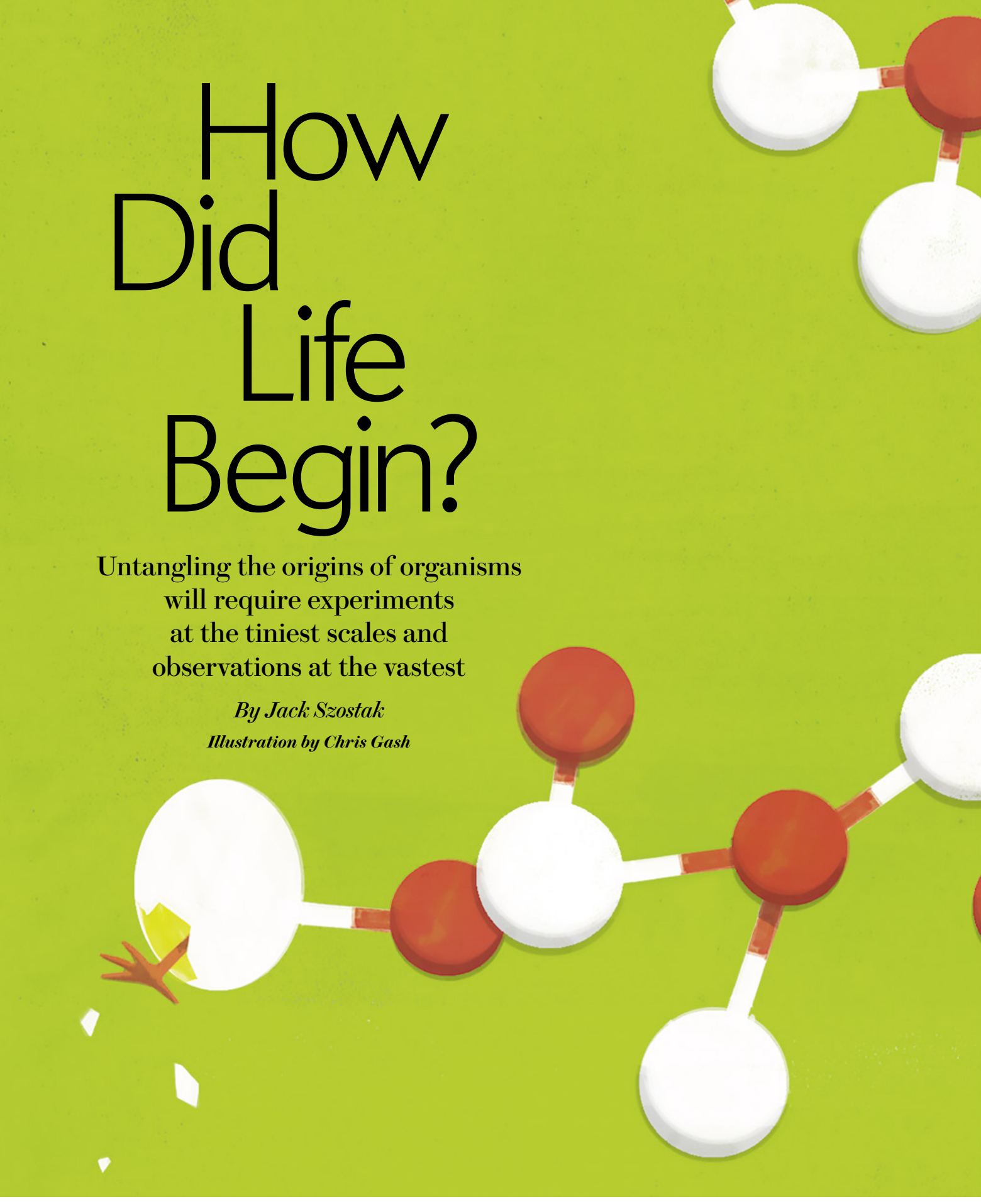
How Did Life Begin?

Untangling the origins of organisms will require experiments at the tiniest scales and observations at the vastest

By Jack Szostak

Illustration by Chris Gash



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IS THE EXISTENCE OF LIFE ON EARTH A lucky fluke or an inevitable consequence of the laws of nature? Is it simple for life to emerge on a newly formed planet, or is it the virtually impossible product of a long series of unlikely events? Advances in fields as disparate as astronomy, planetary science and chemistry now hold promise that answers to such profound questions may be around the corner. If life turns out to have emerged multiple times in our galaxy, as scientists are hoping to discover, the path to it cannot be so hard. Moreover, if the route from chemistry to biology proves simple to traverse, the universe could be teeming with life.

The discovery of thousands of exoplanets has sparked a renaissance in origin-of-life studies. In a stunning surprise, almost all the newly discovered solar systems look very different from our own. Does that mean something about our own, very odd, system favors the emergence of life? Detecting signs of life on a planet orbiting a distant star is not going to be easy, but the technology for teasing out subtle "biosignatures" is developing so rapidly that with luck we may see distant life within one or two decades.

To understand how life might begin, we first have to figure out how—and with what ingredients—planets form. A new generation of radio telescopes, notably the Atacama Large Millimeter/submillimeter Array in Chile's Atacama Desert, has provided beautiful images of protoplanetary disks and maps of their chemical composition. This information is inspiring better models of how planets assemble from the dust and gases of a disk. Within our own solar system, the Rosetta mission has visited a comet, and OSIRIS-REx is on its way back to Earth with samples from an asteroid, which might give us the essential inventory of the materials that came together in our planet.

Once a planet like our Earth—not too hot and not too cold, not too dry and not too wet—has formed, what chemistry must develop to yield the building blocks of life? In the 1950s the iconic Miller-Urey experiment, which zapped a mixture of water and simple chemicals with electric pulses (to simulate the impact of lightning), demonstrated that amino acids, the building blocks of proteins, are easy to make. Other molecules of life turned out to be harder to synthesize, however, and it is now apparent that we need to completely reimagine the path from chemistry to life. The central reason hinges on the versatility of RNA, a very long molecule that plays a multitude of essential roles in all existing forms of life. RNA can not only act like an enzyme but also store and

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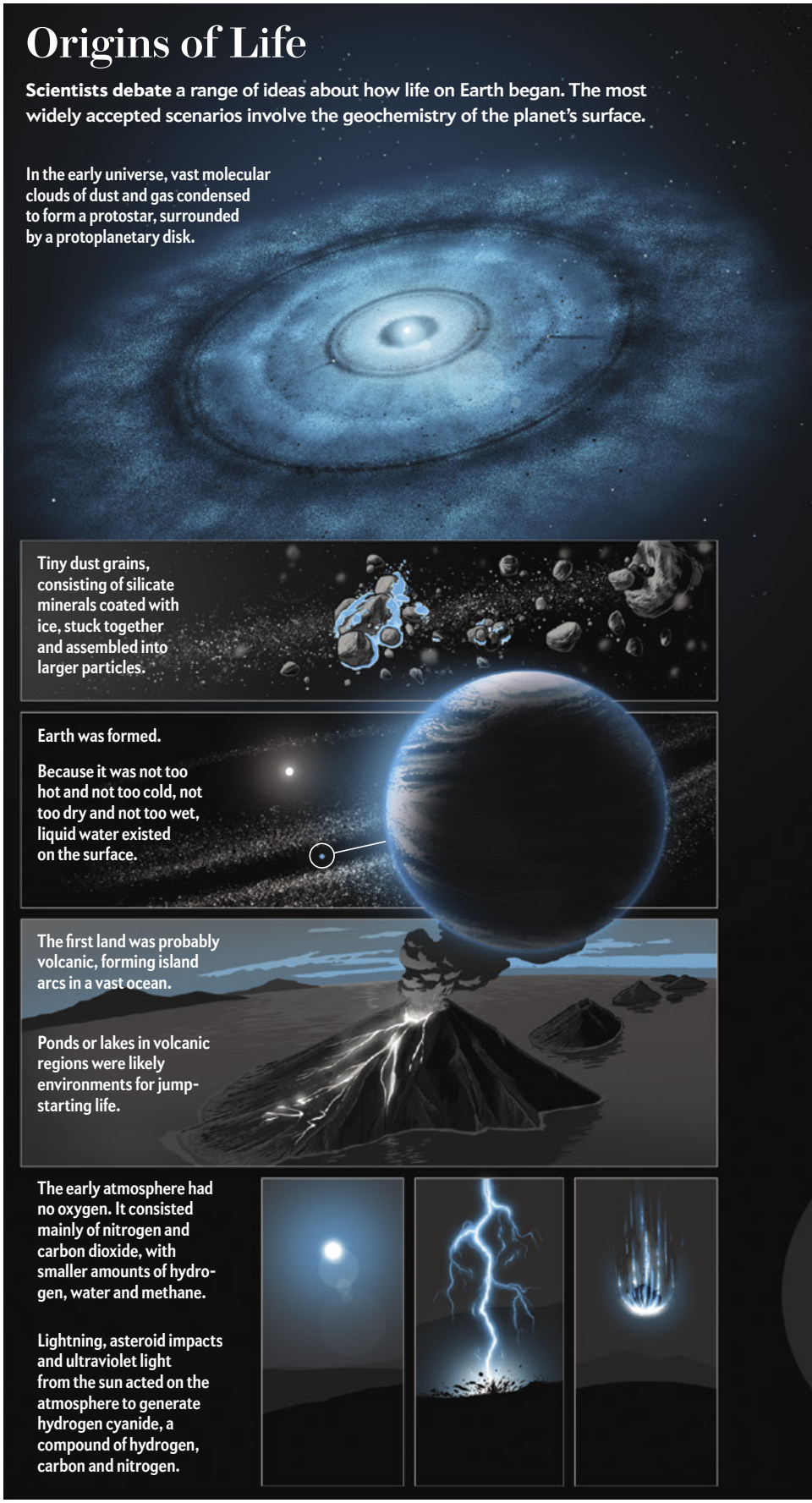
transmit information. Remarkably, all the protein in all organisms is made by the catalytic activity of the RNA component of the ribosome, the cellular machine that reads genetic information and makes protein molecules. This observation suggests that RNA dominated an early stage in the evolution of life.

Today the question of how chemistry on the infant Earth gave rise to RNA and to RNA-based cells is the central question of origin-of-life research. Some scientists think that life originally used simpler molecules and only later evolved RNA. Other researchers, however, are tackling the origin of RNA head-on, and exciting new ideas are revolutionizing this once quiet backwater of chemical research. Favored geochemical scenarios involve volcanic regions or impact craters, with complex organic chemistry, multiple sources of energy, and dynamic light-dark, hot-cold and wet-dry cycles. Strikingly, many of the chemical intermediates on the way to RNA crystallize out of reaction mixtures, self-purifying and potentially accumulating on the early Earth as organic minerals—reservoirs of material waiting to come to life when conditions change.

Assuming that key problem is solved, we will still need to understand how RNA was replicated within the first primitive cells. Researchers are just beginning to identify the sources of chemical energy that could enable the RNA to copy itself, but much remains to be done. If these hurdles can also be overcome, we may be able to build replicating, evolving RNA-based cells in the laboratory—recapitulating a possible route to the origin of life.

What next? Chemists are already asking whether our kind of life can be generated only through a single plausible pathway or whether multiple routes might lead from simple chemistry to RNA-based life and on to modern biology. Others are exploring variations on the chemistry of life, seeking clues as to the possible diversity of life "out there" in the universe. If all goes well, we will eventually learn how robust the transition from chemistry to biology is and therefore whether the universe is full of life-forms or—but for us—sterile.

Jack Szostak is a professor of genetics at Harvard Medical School and one of the recipients of the 2009 Nobel Prize in Physiology or Medicine.


Origins of Life
Scientists debate a range of ideas about how life on Earth began. The most widely accepted scenarios involve the geochemistry of the planet's surface.
In the early universe, vast molecular clouds of dust and gas condensed to form a protostar, surrounded by a protoplanetary disk.
Tiny dust grains, consisting of silicate minerals coated with ice, stuck together and assembled into larger particles.
Earth was formed.
Because it was not too hot and not too cold, not too dry and not too wet, liquid water existed on the surface.
The first land was probably volcanic, forming island arcs in a vast ocean.
Ponds or lakes in volcanic regions were likely environments for jump-starting life.
The early atmosphere had no oxygen. It consisted mainly of nitrogen and carbon dioxide, with smaller amounts of hydrogen, water and methane.
Lightning, asteroid impacts and ultraviolet light from the sun acted on the atmosphere to generate hydrogen cyanide, a compound of hydrogen, carbon and nitrogen.

Graphic by Matthew Twombly

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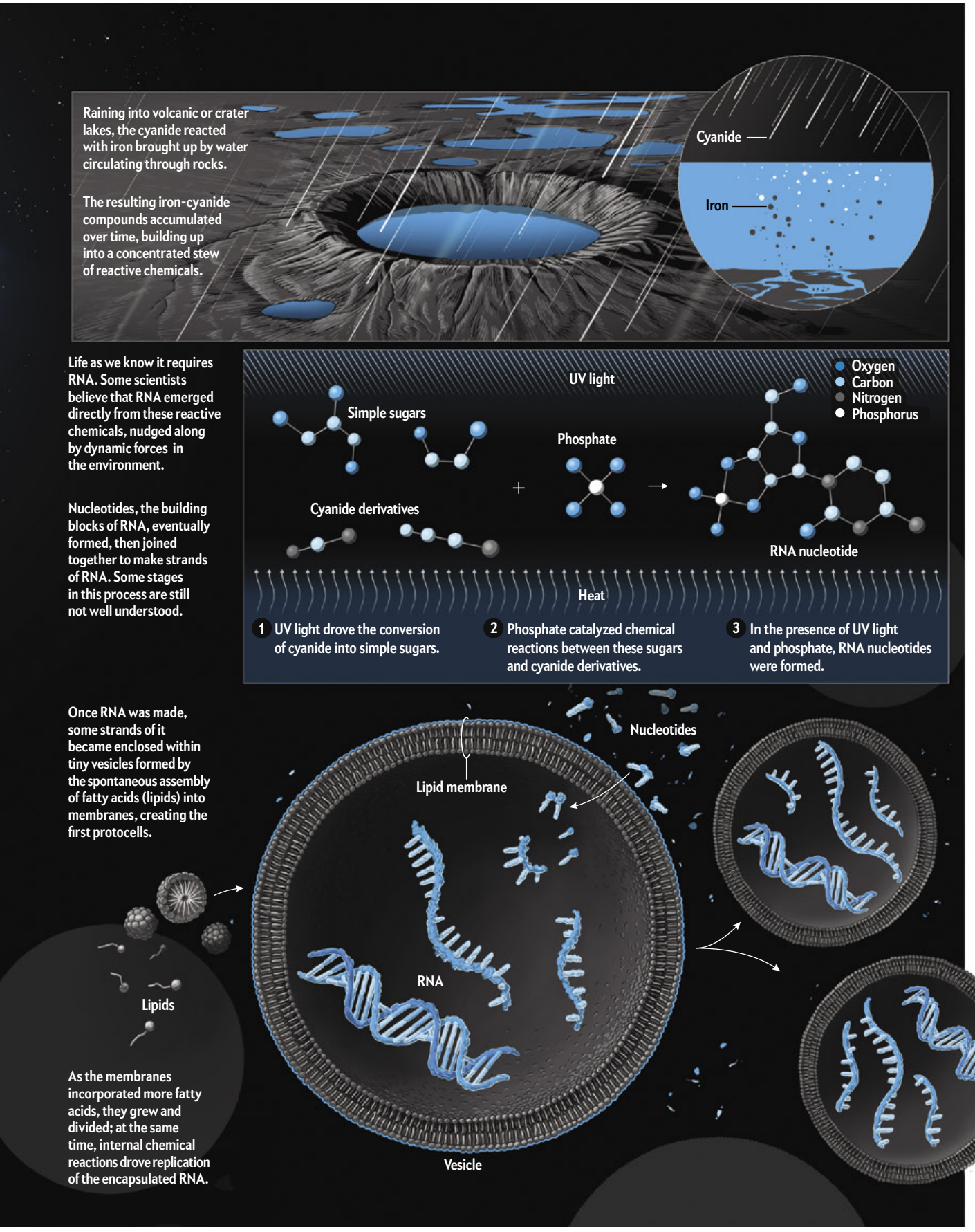
Raining into volcanic or crater lakes, the cyanide reacted with iron brought up by water circulating through rocks.
The resulting iron-cyanide compounds accumulated over time, building up into a concentrated stew of reactive chemicals.
Cyanide
Iron
Life as we know it requires RNA. Some scientists believe that RNA emerged directly from these reactive chemicals, nudged along by dynamic forces in the environment.
Nucleotides, the building blocks of RNA, eventually formed, then joined together to make strands of RNA. Some stages in this process are still not well understood.
UV light
Oxygen
Carbon
Nitrogen
Phosphorus
Simple sugars
Phosphate
Cyanide derivatives
RNA nucleotide
Heat
1 UV light drove the conversion of cyanide into simple sugars.
2 Phosphate catalyzed chemical reactions between these sugars and cyanide derivatives.
3 In the presence of UV light and phosphate, RNA nucleotides were formed.
Once RNA was made, some strands of it became enclosed within tiny vesicles formed by the spontaneous assembly of fatty acids (lipids) into membranes, creating the first protocells.
Nucleotides
Lipid membrane
RNA
Lipids
Vesicle
As the membranes incorporated more fatty acids, they grew and divided; at the same time, internal chemical reactions drove replication of the encapsulated RNA.

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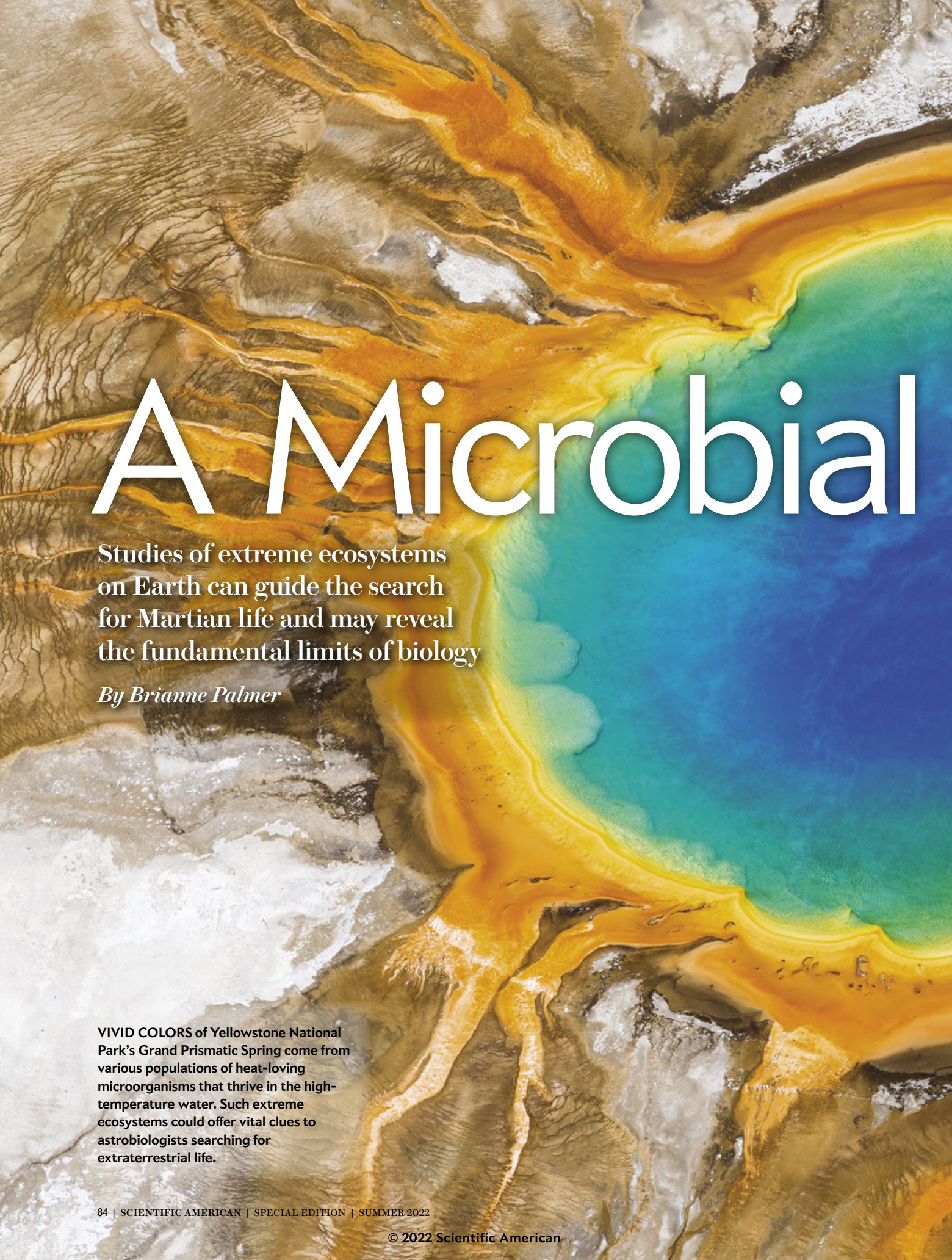
A Microbial

Studies of extreme ecosystems on Earth can guide the search for Martian life and may reveal the fundamental limits of biology

By Brianne Palmer



VIVID COLORS of Yellowstone National Park's Grand Prismatic Spring come from various populations of heat-loving microorganisms that thrive in the high-temperature water. Such extreme ecosystems could offer vital clues to astrobiologists searching for extraterrestrial life.

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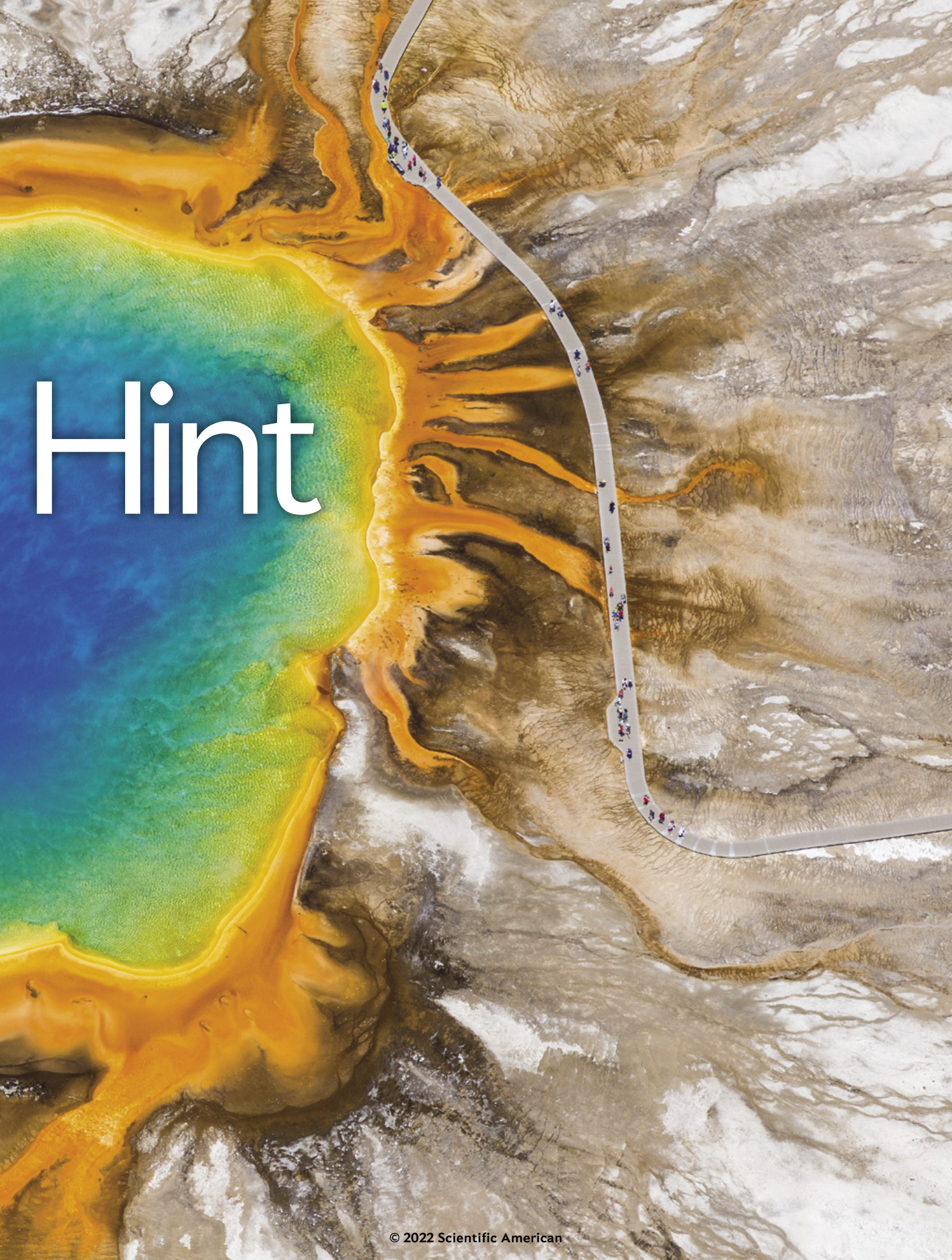

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"I AM *VERY SURE* THAT THERE IS LIFE UP THERE, SOMEWHERE IN OUR SOLAR SYSTEM," says Christine Moissl-Eichinger, a microbiologist at the Medical University of Graz in Austria. But like any scientist, Moissl-Eichinger knows full well that substantial proof is needed for such a substantial claim. So she and others are working to find that proof—both here on Earth and on Mars.

On the Red Planet, NASA's Mars rover Perseverance is searching for fossils and traces of alien biochemistry in Jezero Crater, an ancient lake bed thought to have once offered habitable conditions for microbial life. Back home, microbiologists are investigating oxygen-poor environments that may mimic the habitat of early Mars. This two-pronged approach of grounding scientists' extraterrestrial extrapolations with studies of Earthly analogues could help clarify the bedrock limits for life on rocky planets, greatly aiding the development and execution of future extraterrestrial missions.

The Mars Analogues for Space Exploration project (MASE) was a four-year-long effort that used Earth to understand Mars by analyzing five types of harsh but habitable terrestrial environments that may resemble those that once—or even now—existed on our neighboring planet. Its funding concluded in 2017, but MASE researchers continue to publish results about the habitability of Mars. The study sites included a sulfidic spring, a briny mine, an acidic lake and river, and permafrost. Because of the extreme conditions in these environments, organisms that live here are called extremophiles.

Extremophile research was pioneered by the late Thomas Brock, a microbiologist at the University of Wisconsin–Madison. He found, against all expectations, that certain hardy microbes could thrive in geothermal springs hot enough to poach an egg. The microbiologist's curiosity led to the isolation of a molecule—from a heat-loving bacterium—that is now used in laboratories across the world to amplify and sequence DNA. Brock passed away in April 2021, but his legacy lives on.

Brock published his extremophile findings in April 1969, mere months before humans first walked on the moon. This paved the way for astrobiology, the study of life in all its forms on this planet and elsewhere in the universe. Astrobiology is not about making money off of space travel, says Luke McKay, a researcher at Montana State University, who was not involved with that study or Moissl-Eichinger's recent research. It is about basic science and answering a single, timeless question: Does life exist beyond Earth?

This is a question so profound that so far scientists have only managed to chip away at its edges, with each hard-won revelation usually accompanied by a host of newfound mysteries. Moissl-Eichinger and her team's chief contribution has been their attempt at cultivating extremophiles from MASE's five environments, but even this straightforward task has been devilishly difficult. Out of more than 1,000 different extremophile species gathered from those sites, the team managed to grow just 31 in the lab. This is a common struggle in environmental microbiology. Because these microbes live in extreme places, it is difficult for researchers to re-create the exact conditions they require to thrive. To capture more of the diversity, the team's scientists used genetic sequencing, which allowed them to look at all the microbial DNA in their samples. They specifically searched for genes that may help microbes survive hostile conditions, such as extreme temperatures or the absence of oxygen.

"Cultured [microbial] isolates are not representative of the environment, and that's why it's really cool what they did. By using isolates and sequencing, I think they really tried to cover all the bases," McKay says.

Despite their trouble culturing their extremophile samples, the researchers discovered a vast diversity of microorganisms in all five locations. Even in the most extreme Earthly environments, it seems, life indeed finds a way. Most remarkably, the team's DNA sequencing revealed 34 unique microbial sequences that were conserved in all MASE sites, which is evidence of microbes surviving a combination of extreme environments. According to Moissl-Eichinger, although many microbes are adapted to live in certain conditions such as intense cold or scant oxygen, it is novel to find a group of microbes adapted to survive a combination of these extreme stressors. This ability to survive in many types of environments strengthens the researchers' claims that

Peter Adams/Getty Images (*preceding pages*)

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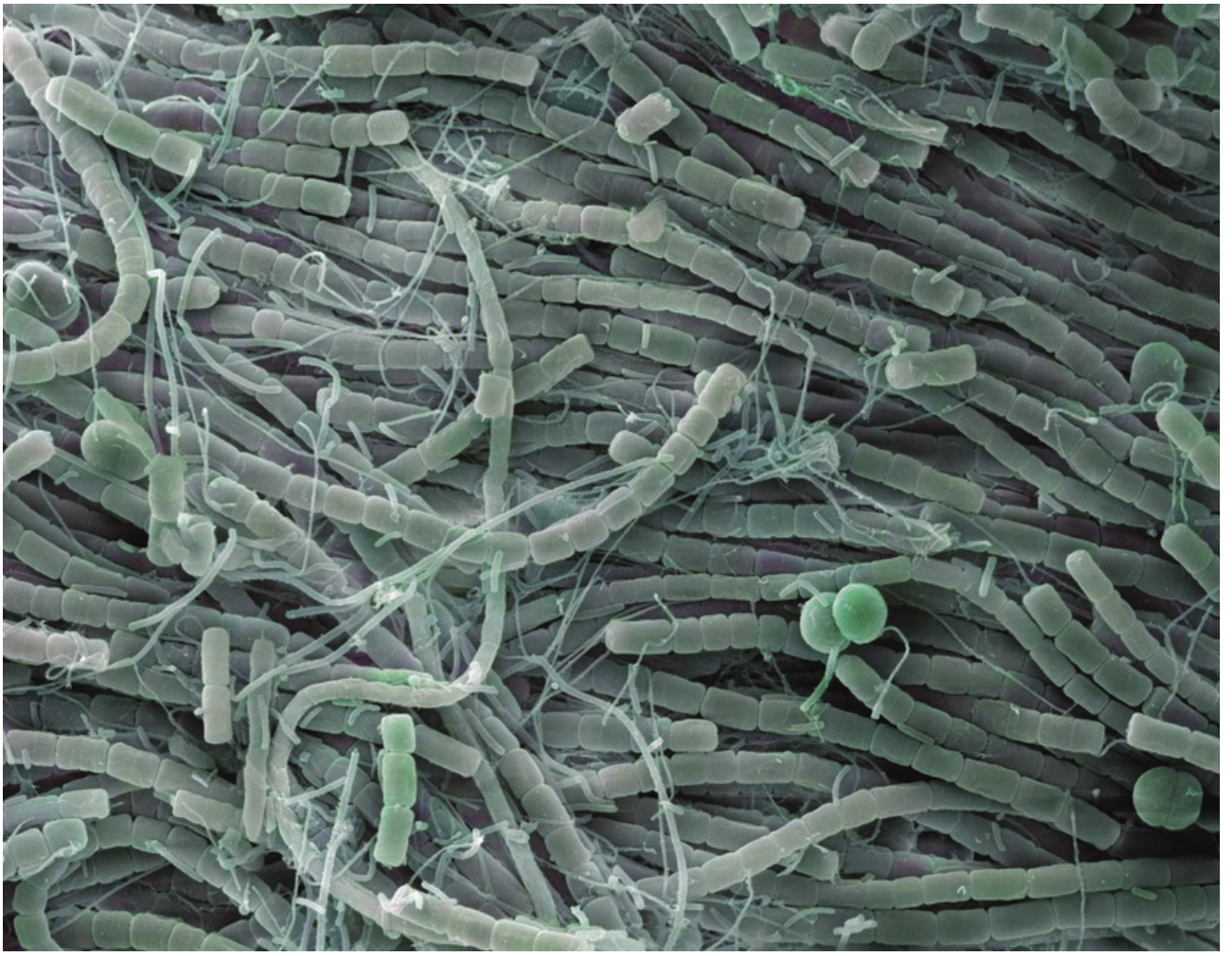

Ted Kinsman/Science Source

A SCANNING ELECTRON microscope (SEM) provides an image of purple sulfur bacteria, algae and unidentified protozoa in a New Mexico hot spring.

similar microbes could exist on Mars—not only in the deep past but even today.

"Microbes are everywhere. They can live in places where we'd expect they could not thrive, but somehow they do," Moissl-Eichinger says. "Of course, on Mars, we do not know if these [extremophiles] are the types of microorganisms we expect to see. They may just be very adapted to life on Earth."

One way these microbes may be particularly adapted to our planet is their dependence on carbon-based compounds, or organic matter. These are the molecular building blocks of life on Earth and may be rare in some otherwise habitable extraterrestrial environments. Some microbes in environments with scarce organic matter can instead get nutrients from inorganic substances, such as ammonia and certain sulfur compounds. Yet all the microbes cultured in the MASE studies relied on organic carbon to survive—even those that could survive without oxygen. According to Moissl-Eichinger, this could be because microbes that consume organic matter grow faster. So with more time, she and her colleagues might successfully culture microbes that get their nutrients from other chemical sources, potentially revealing new biochemical pathways and ecological niches to consider when searching for life on Mars.

"We are far away from understanding what microbes could look like on Mars and how we can find them. But of course, research always gives a little piece by piece, and at some point, the picture gets fuller," Moissl-Eichinger says.

Understanding how all these disparate pieces fit together may change our definition of what it means to be alive. According to McKay, extraterrestrial environments for life may be like those found on Earth, or they could differ vastly. At present, given our sample size of only one confirmed life-bearing world, both possibilities appear equally plausible.

"If [extraterrestrial life] is too [similar] to our life on Earth, people will argue that it is something that we brought with us. But if it is too different, will we be able to see it?" Moissl-Eichinger says. "Now that is the question that drives us." SA

Brianne Palmer is a Ph.D. student at San Diego State University and the University of California, Davis, studying how soil microbes respond to fire. She frequently writes about the intersection of technology and the environment.

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OPINION

How to Search for Life as We Don't Know It

Much of astrobiology is focused on looking for organisms with chemistry similar to ours—but there could well be other kinds

By Avi Loeb

IN MY FRESHMAN SEMINAR AT HARVARD University in spring 2021, I mentioned that the nearest star to the sun, Proxima Centauri, emits mostly infrared radiation and has a planet, Proxima b, in the habitable zone around it. As a challenge to the students, I asked: "Suppose there are creatures crawling on the surface of Proxima b. What would their infrared-sensitive eyes look like?" The brightest student in class responded within seconds with an image of the mantis shrimp, which possesses infrared vision. The shrimp's eyes look like two Ping Pong balls connected with cords to its head. "It looks like an alien," she whispered.

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When trying to imagine something we've never seen, we often default to something we have seen. For that reason, in our search for extraterrestrial life, we are usually looking for life as we know it. But is there a path for expanding our imagination to life as we don't know it?

In physics, an analogous path was already established a century ago and turned out to be successful in many contexts. It involves conducting laboratory experiments that reveal the underlying laws of physics, which in turn apply to the entire universe. For example, around the same time the neutron was discovered in the lab of James Chadwick in 1932, Lev Landau suggested that there might be stars made of neutrons. Astronomers realized subsequently that there are, in fact, some 100 million neutron stars in our Milky Way galaxy alone—and a billion times more in the observable universe. Relatively recently, the LIGO experiment detected gravitational-wave signals from collisions between neutron stars at cosmological distances. It is now thought that such collisions produce the precious gold that is forged into wedding bands. The moral of this story is that physicists were able to imagine something new in the universe at large and search for it in the sky by following insights gained from lab experiments on Earth.

Although the surfaces of planets and asteroids can be explored remotely for biological signatures, extraterrestrial life might be most abundant under the surface.

The search for extraterrestrial life can follow a similar approach. By creating synthetic life in various ways from a soup of chemicals in the lab, we might be able to imagine new environments where life might occur differently than on Earth. The situation is similar to composing a recipe book with prescriptions for baking different types of cakes. To write a rich recipe book, we need to experiment with many types of chemicals. And, as I noted in a paper with Manasvi Lingam, this experimentation may use fluids other than water, which is considered essential for life as we know it.

One of my Harvard colleagues, the Nobel laureate Jack Szostak, is getting close to creating synthetic life in his lab. Any success with a single recipe may suggest variations that would produce a diversity of outcomes, to be assembled into our recipe book for synthetic life. By identifying suitable environmental conditions from our lab experiments, we can later search for real systems where they are realized in the sky, just as in the case of neutron stars.

In following this approach, we should be as careful as we are in tapping nuclear energy. Creating artificial variants of life in our labs brings the risk of causing an environmental disaster, as imagined in the story of Frankenstein. Such experimentation must be performed in isolated environments so that mishaps with life as we don't know it will not endanger the life we know.

Although the surfaces of planets and asteroids can be explored remotely for biological signatures, extraterrestrial life might be most abundant under the surface. Habitable conditions could exist in the oceans that lie under thick icy surfaces, not only within moons such as Saturn's Enceladus and Jupiter's Europa but also inside free-floating objects in interstellar space. In other research with Lingam, we showed that the number of life-bearing objects could exceed the number of rocky planets in the habitable zone around stars by many orders of magnitude.

The adaptation of life to extreme environments could take exotic forms, as exemplified by extremophiles on Earth. For example, frozen microscopic animals were recently discovered to survive 24,000 years in the Siberian permafrost, and microbial life was found to persist 100 million years underneath the seafloor. These microbes were born during the warm Cretaceous period when dinosaurs dominated Earth.

In the solar system, the closest conditions to Earth's were realized on its nearest neighbors, Venus and Mars. NASA has selected two new missions to study Venus, and its Perseverance rover is searching for traces of life on Mars. If extraterrestrial life is found, the key follow-up question is whether it is life as we know it. If not, we will realize that there are multiple chemical pathways to natural life. But if we find evidence for Martian or Venusian life that resembles terrestrial life, then that might indicate a special preference for life as we know it. Alternatively, life could have been transported by rocks that traveled between planets through a process called panspermia. My student Amir Siraj and I wrote a paper showing that the transfer of life could have been mediated by planet-grazing asteroids. We should also keep in mind the very remote possibility that life was seeded in the inner solar system by an "extrasolar gardener," namely, through "directed panspermia."

My most vivid childhood memory is of dinner conversations in which the adults in the room pretended to know much more than they actually did. This was undoubtedly a form of "intellectual makeup" that they wore to improve their appearance. And if I asked a question to which these pretenders had no ready answer, they would dismiss it as irrelevant. My experience as a senior scientist is no different, especially when asking the question: "Are we the smartest kid on the cosmic block?"

Science offers the privilege of maintaining our childhood curiosity. The advance of scientific knowledge through experimentation cannot be stopped. Here's hoping that we will find a recipe for artificial life that will allow us to imagine something far more intelligent than the natural life we have encountered so far. This will be a humbling experience. But even if we do not discover this supreme intelligence in our labs, its by-products may just show up in our sky as mail posted from faraway neighborhoods in the Milky Way. And we'll be searching for that through the telescopes of our Galileo Project, launched in 2021. SA

Avi Loeb is former chair (2011–2020) of the astronomy department at Harvard University, founding director of Harvard's Black Hole Initiative and director of the Institute for Theory and Computation at the Center for Astrophysics | Harvard & Smithsonian. He also chairs the Board on Physics and Astronomy of the National Academies and the advisory board for the Breakthrough Starshot project, and he is a member of the President's Council of Advisors on Science and Technology. Loeb is the best-selling author of *Extraterrestrial: The First Sign of Intelligent Life Beyond Earth* (Houghton Mifflin Harcourt).

Getty Images *(preceding pages)*

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Earth before Us

A provocative study examines whether a prehuman civilization existed

By Steven Ashley

ONE OF THE CREEPIER CONCLUSIONS DRAWN BY SCIENTISTS STUDYING the Anthropocene—the proposed epoch of Earth's geologic history in which humankind's activities dominate the globe—is how closely today's industrially induced climate change resembles conditions seen in past periods of rapid temperature rise.

"These 'hyperthermals,' the thermal-maximum events of prehistory, are the genesis of this research," says Gavin Schmidt, climate modeler and director of the NASA Goddard Institute for Space Studies. "Whether the warming was caused by humans or by natural forces, the fingerprints—the chemical signals and tracers that give evidence of what happened then—look very similar."

The canonical example of a hyperthermal is the Paleocene-Eocene Thermal Maximum (PETM), a 200,000-year period that occurred some 55.5 million years ago when global average temperatures rose by five to eight degrees Celsius (nine to 14 degrees Fahrenheit). Schmidt has pondered the PETM for his entire career, and it was on his mind one day in 2017 when University of Rochester astrophysicist Adam Frank paid him a visit.

Frank came to his office to discuss the idea of studying global warming from an "astrobiological perspective"—that is, investigating whether the rise of an alien industrial civilization on an exoplanet might necessarily trigger climate changes similar to those we see during Earth's own Anthropocene. But almost before Frank could describe how one might search for the climatic effects of industrial "exocivilizations" on newly discovered planets, Schmidt caught him up short with a surprising question: "How do you know we're the only time there's been a civilization on our own planet?"

Frank considered a moment before responding with a question of his own: "Could we even tell if there had been an industrial civilization [long before this one]?"

Their subsequent attempt to address both questions yielded a provocative paper on the possibility that Earth might have spawned more than one technological society during its 4.5-billion-year history. And if indeed some such culture arose on Earth in the murky depths of geologic time, how might scientists today discern signs of that incredible development? Or, as they put it in the paper: "If an industrial civilization had existed on Earth many millions of years prior to our own era, what traces would it have left and would they be detectable today?"

Schmidt and Frank began by forecasting the geologic fingerprints the Anthropocene is likely to leave behind—such as hints of soaring temperatures and rising seas laid down in beds of sedimentary rock. These features, they noted, are very similar to the geologic leftovers of the PETM and other hyperthermal events. They then considered what tests could plausibly distin-

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If some technological culture arose on Earth in the murky depths of geologic time, how might we today discern signs of that incredible development?

guish an industrial cause from otherwise naturally occurring climate changes. "These issues have never really been addressed to any great extent," Schmidt notes. And that goes not only for scientists but evidently for science-fiction writers as well, he adds: "I looked back into the science-fiction literature to try to find the earliest example of a story featuring a nonhuman industrial civilization on Earth. The earliest I could find was in a *Doctor Who* episode."

That 1970 episode of the classic TV series involves the present-day discovery of "Silurians"—an ancient race of technologically advanced, reptilian humanoids who predated the arrival of humans by hundreds of millions of years. According to the plot, these highly civilized saurians flourished for centuries until Earth's atmosphere entered a period of cataclysmic upheaval that forced *Homo reptilia* to go into hibernation underground to wait out the danger. Schmidt and Frank paid tribute to the episode in the title of their paper: "The Silurian Hypothesis."

LOST IN STRATA

ANY PLAUSIBILITY of the Silurian hypothesis stems chiefly from the vast incompleteness of the geologic record, which only gets sparser the further back in time you go.

Today less than 3 percent of Earth's surface is urbanized, and the chance that any of our great cities would remain over tens of millions of years is vanishingly low, says geologist Jan Zalasiewicz of the University of Leicester in England. A metropolis's ultimate fate, he notes, mostly depends on whether the surrounding surface is subsiding (to be locked in rock) or rising (to be eroded away by rain and wind). "New Orleans is sinking; San Francisco is rising," he says. The French Quarter, it seems, has much better chances of entering the geologic record than Haight-Ashbury.

"To estimate the odds of finding artifacts," Schmidt says, "the back-of-the-envelope calculation for dinosaur fossils says that one fossil emerges every 10,000 years." Dinosaur footprints are rarer still.

"After a couple of million years," Frank says, "the chances are that any physical reminder of your civilization has vanished, so you have to search for things like sedimentary anomalies or isotopic ratios that look off." The shadows of many prehuman civilizations could, in principle, lurk hidden in such subtleties.

But exactly what we would look for depends to some degree on how an Earthly but alien technological culture would choose to behave. Schmidt and Frank decided the safest assumption to make would be that any industrial civilization now or hundreds of millions of years ago should be hungry for energy. That means any ancient industrial society would have developed the capacity to widely exploit fossil fuels and other power sources, just as we did. "We'd be looking for globalized effects that would leave a worldwide trace"—planetary-scale physical-chemical tracers of energy-intensive industrial processes and their wastes, Schmidt says.

Next comes the issue of longevity—the longer a civilization's energy-intensive period persists and the more its demands increase, the more obvious its presence should become in the geologic record. Consider our own industrial age, which has existed for only about 300 years out of a multimillion-year history of humanity. Now compare that minuscule slice of time with the half a billion years or so that creatures have lived on land. Humanity's present rapacious phase of fossil-fuel use and environmental degradation, Frank says, is unsustainable for long periods. In time, it will diminish either by human choice or by the force of nature, making the Anthropocene less of an enduring era and more of a blip in the geologic record. "Maybe [civilizations like ours] have happened multiple times, but if they each only last 300 years, no one would ever see them," Frank says.

Taking all this into consideration, what remains is a menu of diffuse long-lived tracers including fossil-fuel combustion residues (carbon, primarily), evidence of mass extinctions, plastic pollutants, synthetic chemical compounds not found in nature and even transuranic isotopes from nuclear fission. In other words, what we would need to look for in the geologic record are the same distinctive signals that humans are laying down right now.

SIGNS OF CIVILIZATION

FINDING SIGNS of an altered carbon cycle would be one big clue to previous industrial periods, Schmidt says. "Since the mid-18th century, humans have released half a trillion tons of fossil carbon at high rates. Such changes are detectable in changes in the carbon isotope ratio between biological and inorganic carbon—that is, between the carbon incorporated into things like seashells and that which goes instead into lifeless volcanic rock."

Another tracer would be distinctive patterns of sediment deposition. Large coastal deltas would hint at boosted levels of erosion and rivers (or engineered canals) swollen from in-

Michael Osadciw/University of Rochester

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creased rainfall. Telltale traces of nitrogen in the sediments could suggest the widespread use of fertilizer, fingering industrial-scale agriculture as a possible culprit; spikes in metal levels in the sediments might instead point to runoff from manufacturing and other heavy industry.

More unique, specific tracers would be nonnaturally occurring, stable synthetic molecules such as steroids and many plastics, along with well-known pollutants, including polychlorinated biphenyls (toxic chemical compounds from electrical devices) and chlorofluorocarbons (ozone-eating molecules from refrigerators and aerosol sprays).

The key strategy in distinguishing the presence of industry from nature, Schmidt notes, is developing a multifactor signature. Absent artifacts or convincingly clear markers, the uniqueness of an event may well be seen in many relatively independent fingerprints as opposed to the coherent set of changes that are seen to be associated with a single geophysical cause.

"I find it amazing that no one had worked all this out before, and I'm really glad that somebody has taken a closer look at it," says Pennsylvania State University astronomer Jason Wright, who in 2017 published "a fluffy little paper" exploring the counterintuitive notion that the best place to find evidence of any of Earth's putative prehuman civilizations may well be off-world. If, for instance, dinosaurs built interplanetary rockets, presumably some remnants of that activity might remain preserved in stable orbits or on the surfaces of more geologically inert celestial bodies such as the moon.

"Look, 200 years ago the question of whether there might be a civilization on Mars was a legitimate one," Wright says. "But once the pictures came out from interplanetary probes, that was settled for good. And that view became ingrained, so now it's not a valid topic for scientific inquiry; it's considered ridiculous. But no one's ever put the actual scientific limits on it—on what may have happened a long time ago."

Wright also acknowledges the potential for this work to be misinterpreted. "Of course, no matter what, this is going to be interpreted as 'Astronomers Say Silurians Might Have Existed,' even though the premise of this work is that there is no such evidence," he says. "Then again, absence of evidence is not evidence of absence."

Steven Ashley is a freelance science-technology writer and editor.

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Finding Life off Earth

Avi Loeb's controversial initiative is targeting unidentified phenomena in Earth's skies and beyond

By Adam Mann

AVI LOEB in the observatory near his office in Cambridge, Mass., in January 2019

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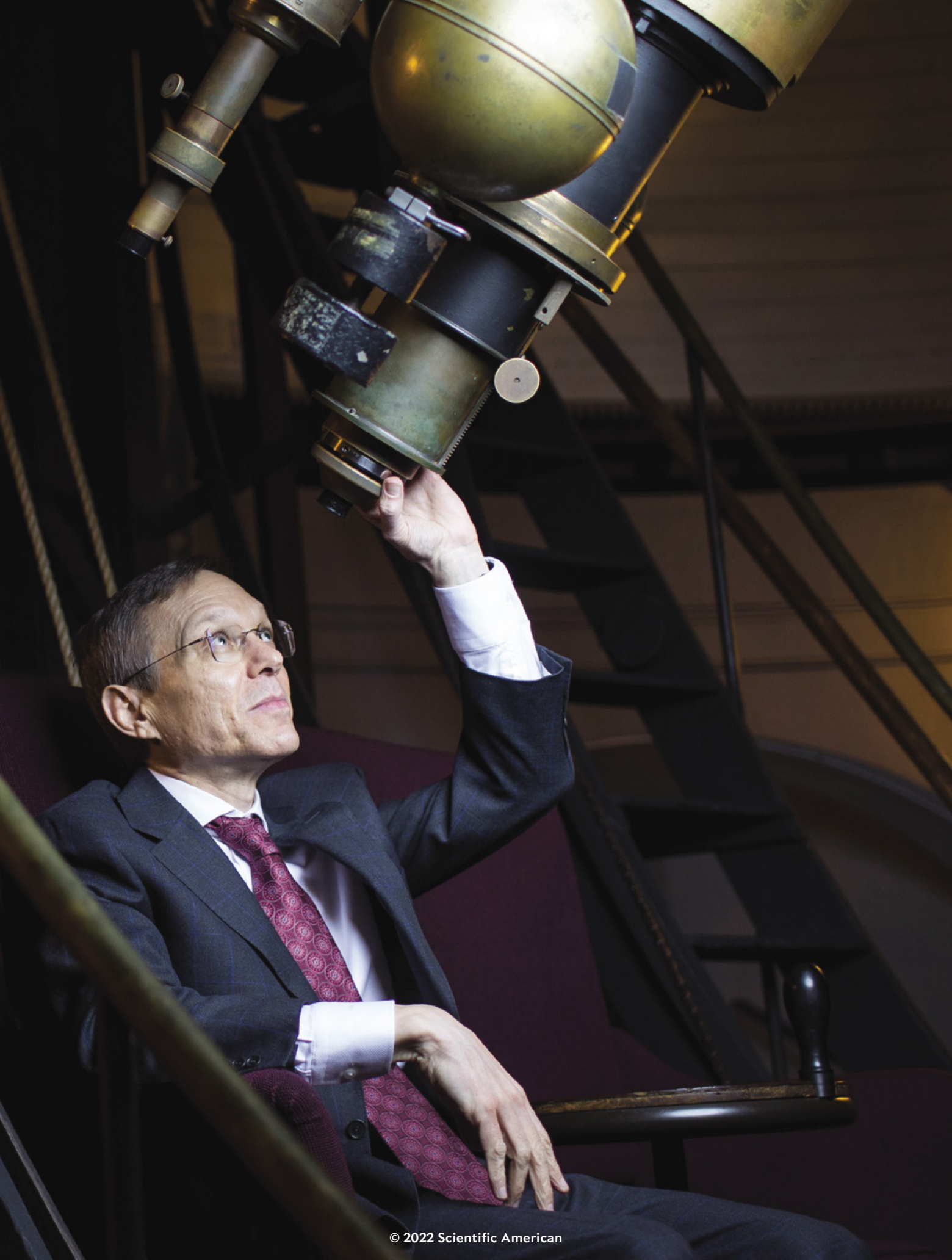

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WHAT EXACTLY IS HARVARD THEORETICAL ASTROPHYSICIST AVI LOEB doing co-founding a $1.755-million academic effort to look for UFOs? In July 2021 Loeb revealed the Galileo Project, which aims to develop an artificial-intelligence-powered network of telescopes that can search for evidence of technological alien civilizations on or near Earth.

The project has received mixed criticism from outside researchers, who maintain that although there is no harm in at least looking for such things in a rigorous manner, the possibility of finding anything seems slim.

Galileo is an outgrowth of Loeb's particular passion—making the case that 'Oumuamua, the first interstellar comet ever discovered, might actually be a probe from an intelligent species looking to learn about our solar system. For the past few years he has been trumpeting the idea both in the scientific literature and in a nonfiction book, *Extraterrestrial*.

While on a publicity tour for the book, Loeb says, he was contacted by many people interested in UFOs—which are now more politely referred to as unidentified aerial phenomena, or UAPs. Several of those people turned out to be both wealthy and generous, gifting him with large sums of money to use for further, more formal, investigations.

"I always emphasize the fact that it's not a philosophical question whether an object is an artifact from a technological civilization," Loeb says. "It's very easy to answer by taking a high-resolution photograph."

That is what he and his research partners at Galileo hope to do by building small arrays of instruments that would continuously scan the skies to capture data about anything out of the ordinary. The project also intends to develop sensors to hunt for any unusual, artificial and potentially alien satellites orbiting Earth, as well as to look for other 'Oumuamua-like interstellar objects to study in greater detail.

Despite the project's outlandish focus, scientists not associated with the group think Galileo can provide useful information. "In the sense that this could serve to legitimize those kinds of investigations, it can be a very positive thing," says Lucianne Walkowicz, an astronomer at the Adler Planetarium in Chicago.

"I'm glad to see Avi and others not being afraid of silly associations," says Jason Wright, a Pennsylvania State University astrophysicist who works on the search for extraterrestrial intelligence (SETI). "So much of UFO stuff is far from the way we actually do science; it's hard to associate yourself with it and still be taken seriously. I appreciate that Avi is going to do some systematic data collection and study it with a clean sheet."

Both Walkowicz and Wright emphasize that they don't believe UAPs to have exotic extraterrestrial explanations, considering them much more likely to be mundane things such as planes, birds, insects, meteors or atmospheric phenomena. Given their highly random nature—most eyewitness accounts describe them appearing out of nowhere and disappearing just as quickly—building detectors to monitor them might be quite difficult.

"It's really hard to see how you establish a search strategy that would have a chance of seeing one," says Jonathan McDowell, an astrophysicist at the Center for Astrophysics | Harvard & Smithsonian. "I suspect there are more well-motivated SETI projects, or even UFO-search projects, that could be funded for less money."

UAPs have been having something of a cultural moment. The Department of Defense and the Office of the Director of National Intelligence released a highly anticipated report in June 2021 on their own investigations into the phenomena. The government concluded that most of the events were likely terrestrial in origin—things such as weather balloons and foreign drones—but added they merited further study.

Adam Glanzman/Getty Images *(preceding pages)*

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Galileo is intended to do that beyond the confines of classified military information collection, producing openly accessible data that will be published in peer-reviewed scientific journals. "The Pentagon has a $22-million budget to study UAPs, and I'm not sure what that produced," says astrophysicist Amir Siraj, also at Harvard, who works on the project. "The hope is that with less money we will be able to produce better results."

A modern one-meter telescope capable of resolving pinhead-size details on a human being from a kilometer away can be ordered off-the-shelf for as little as $500,000, Loeb says. He has secured enough money for a few such instruments, although he hopes to eventually raise 10 times more funding and place multiple sensors at various still to be chosen locations that will be aided by detectors using infrared and radar.

The project has assembled a wide array of technicians, instrumentalists and other scientists as part of its research team. It is currently backed by affluent individuals who mainly made their money developing industrial equipment for chemistry applications, among them chemist and entrepreneur Frank H. Laukien. Loeb says the funding comes with "no strings attached in a way that allows me complete freedom," although several early supporters had seats on a philanthropic advisory board for Galileo.

How long such funders will stay with the project, and whether Loeb will convince others to donate additional capital, remains to be seen. Given that it will take time to develop and test software that can filter out the multitude of objects constantly whizzing overhead, it appears unlikely that Galileo will have much to show anytime soon, says Mick West, a skeptical investigator who produces explanatory films about UAP videos.

"The issue with UFOs is they exist in the low-information zone," West adds. "They have historically always been just too far away to resolve what they are, and every time you have a better camera, they get farther away."

Still, West welcomes more investigation. "Right now we don't have the evidence, and when we do have the evidence, it's quite contentious," he says. "I would prefer things to be less ambiguous."

Galileo is not entirely novel in its proposals. A project called Sky Hub sought to use civilian-owner sensors and machine learning to catalog events in the sky that might have placed limits on whether any given occurrence indicated visitors from another planet. Instruments such as the upcoming Vera C. Rubin telescope already are planned to look for new interstellar comets and asteroids, and the European Space Agency is developing its Comet Interceptor mission, which could launch in 2029 to wait for a possible rendezvous with some as yet undiscovered suitable interstellar target.

As far as potential alien objects in low Earth orbit, there is already an enormous military and civilian array dedicated to monitoring the space around our planet, which is littered with more than 20,000 known satellites and other entities. Loeb "basically has to replicate the entire space-surveillance network and look for the outliers," McDowell says. "It's a very hard and expensive project to do right, and the chance of finding something seems remote."

Finally, there is the issue of Loeb's personality. In recent years he has increasingly alienated himself from the astronomical community, painting himself as a brave free thinker challenging the closed-minded dogmas of the broader scientific world.

The Galileo Project's tagline—"Daring to Look through New Telescopes"—is meant to evoke the scientist Galileo Galilei, who helped to upend the geocentric model of the universe with his observations. But Loeb himself is not exactly a marginalized outsider.

> Might 'Oumuamua, the first interstellar comet ever discovered, be a probe looking to learn about our solar system?

"Avi does this thing where he implies that he's this iconoclast who's pushing the boundaries of what is acceptable in science," Walkowicz says. "But he has nothing at risk. He's a tenured Harvard professor."

In a February 2021 Zoom call, Loeb grew extremely confrontational toward SETI pioneer Jill Tarter, berating her and the rest of the community for not giving greater support to his proposals. (He has since apologized both publicly and privately to Tarter.)

Few academics, including those working with the project, think they will discover aliens here on Earth. "If we were actually being visited by extraterrestrials, then I would expect we'd be seeing a lot of 'museum artifacts,'" says Abel Méndez, an astrobiologist at the University of Puerto Rico, referring to the four billion years of prior history in which aliens could have landed something like a Mars rover, with its heat shield, casing and parachutes, on Earth's surface.

Whether Galileo will ultimately yield anything of interest remains to be seen. Loeb has brought together a large group to help him in his quest, yet it is always possible that his own viewpoints hinder him in certain ways.

"Is he a voice crying out the truth in the wilderness, or is he a bit of a crank?" West asks. "Time will tell." SA

Adam Mann is a journalist specializing in astronomy and physics. His work has appeared in *National Geographic*, the *Wall Street Journal*, *Wired*, and elsewhere.

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Even if the Milky Way is teeming with spacefaring aliens, we should not be surprised that Earth remains unvisited

The Galactic Archipelago

By Caleb Scharf

Illustration by María Corte

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ON THE 15TH OF JANUARY IN 1790, NINE MUTINEERS FROM HMS *Bounty,* 18 people from Tahiti and one baby arrived on Pitcairn Island—one of the most isolated habitable places on the planet. Surrounded by the southern Pacific Ocean and with hundreds of miles of open water between it and the nearest other islands, Pitcairn is the epitome of solitude.

Before the *Bounty* escapees showed up, the island may not have seen human occupation of any kind since the 1400s, when it was still inhabited by Polynesians. That community perhaps existed for centuries—centuries that seem to have culminated with a depletion of natural resources, as well as conflicts on other, distant islands that cut off lines of trade and supply, leading to the effective extinction of Pitcairn's human occupants. What was, at least superficially, a habitable place had become unsustainable, until the arrival of the *Bounty* on that fateful day in 1790. Remarkably, it took another 18 years for any other ship to drop anchor at Pitcairn, even though the settlers recorded sightings of vessels passing in the distance.

The story of Pitcairn is just one extreme example of the unusual dynamics of human occupation across the southern Pacific. Within the regions of Polynesia, Micronesia and Melanesia, there are tens of thousands of islands scattered across millions of square miles of ocean. Many are barely more than a protuberance of rock and coral, and even the habitable spots are not all inhabited at any given time. But taken together, they represent a vast landscape of potential settlement and civilization for people motivated to navigate across Earth's watery depths.

The parallels between this unmistakably terrestrial environment and our cosmic surroundings are striking. In the Milky Way galaxy, there are perhaps as many as 300 billion stars. The best estimates from exoplanet-hunting efforts, such as those undertaken with NASA's Kepler space telescope, suggest that within this ocean of stellar bodies there may be more than 10 billion small, rocky worlds in orbital configurations conducive to temperate surface conditions. Like the islands of Earth, these exoplanetary specks might both generate and support living systems and could provide a network of waypoints for any species determined to migrate across interstellar space. And that is where things get really interesting.

JUST AS WESTERN EUROPEANS EVENTUALLY REALIZED that the peoples of the southern Pacific had spread across its thousands of miles of ocean on simple vessels gliding along at just a few knots, we can now see that spreading across our galaxy need not require much more than persistence and a modest amount of cosmic time.

Most famously, over a lunch in 1950 with fellow scientists, physicist Enrico Fermi first recognized this fact and—as the story goes—blurted out, "Don't you ever wonder where everybody is?" The "everybody" in this case was any spacefaring species, and the question developed over time into the equally famous, albeit somewhat mislabeled, Fermi paradox: unless technologically proficient species are vanishingly rare, they should have spread practically everywhere across the galaxy by now, yet we see no evidence for them. Fermi, renowned for his ability to carry out so-called back-of-the-envelope calculations in his head, had figured out in approximate terms that the Milky Way could be settled in the blink of a cosmic eye when each tick of the galactic clock accounts for millions of years.

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In 1975 astrophysicist Michael Hart produced the first properly quantitative and nuanced study of this idea, in which he put forward what has become known as Hart's "fact A." This refers to the absence of aliens on Earth today. That unassailable fact (for most level-headed people) led Hart to the conclusion that no other technological civilizations currently exist—or have ever existed—in our galaxy. The key to this assertion, much as with Fermi's original insight, lies in the relatively short amount of time it would apparently take for a species to spread across the Milky Way's 100,000-light-year girth even using modest, far-slower-than-light propulsion systems.

Physicist Frank Tipler also studied the problem, and he reported on his work in 1980, demonstrating, much like Hart, that in a few million years suitably motivated aliens could indeed visit everywhere. Given that our solar system has been around for 4.5 billion years and that the Milky Way assembled at least 10 billion years ago, there has been more than enough time for species to wind up on all inhabitable worlds.

Critically, though, these investigations considered the spread of life somewhat differently. Hart assumed a process of settlement "in the flesh" by a biological species, whereas Tipler imagined star-hopping swarms of self-replicating machine probes that would spread without restraint. In most settlement scenarios, the stellar systems and their planets become inhabited, if they were not already, and then serve as the next base of operations for launching onward to new systems. For Tipler's self-replicating machines, the primary limits to their expansion would be the availability of sufficient energy and raw materials for making each subsequent generation.

These radically different approaches highlight the challenges of making meaningful statements about interstellar migration. There are always a lot of big assumptions in any study like these. Some are reasonable and easily justifiable, but others are trickier. For example, all scenarios involve guesses about the scope of the technology used for interstellar travel. Furthermore, when the species is "along for the ride" rather than sending out sophisticated robotic emissaries, the most fundamental assumption is that living things can survive any kind of interstellar travel at all.

We know that traveling at even a paltry 10 percent of the speed of light requires some pretty wild technology—for example, fusion-bomb propulsion or colossal laser-driven light sails. There also has to be shielding from the hull-eroding impacts of interstellar gas atoms, as well as from starship-destroying crumbs of rock, each of which carries the punch of a bomb for a spacecraft at any decent fraction of light speed. Traveling at more modest speeds is potentially much safer but results in transit times between stars of centuries or millennia—and it is far from obvious how to keep a crew alive and well for time spans that may greatly exceed individual lifetimes.

The most contentious assumptions, though, revolve around questions of motivation and the projections we make about the longevity of entire civilizations and their settlements. For example, if an alien species is simply not interested in reaching other stars, the whole idea of galactic settlement literally stalls. This was one argument put forward by Carl Sagan and William Newman in 1983 as a rebuttal to what they called the "solipsist approach" to extraterrestrial intelligence. But as my colleague astronomer Jason Wright of the Pennsylvania State University points out, this kind of proposition is itself arguably a "monocultural fallacy." To put this another way: it seems impossible to speculate with any accuracy about the behavior of an entire species as if it were thinking with one unified mind. We humans certainly do not fit in that box. And even if the vast majority of the Milky Way's putative spacefaring civilizations do not attempt galactic diasporas, all it may take is one culture going against the grain to spread signs of life and technology across hundreds of billions of star systems.

In fact, the history of Fermi's paradox is awash with diverse debates on its underlying suppositions, as well as with a huge variety of posited "solutions." Few, if any, of these solutions are readily testable. Although some include ideas that are pretty straightforward, others are strictly science fiction. For example, it could be that the cost in resources of attaining the ability to rapidly traverse interstellar space is too high even for a superbly technological species. That could certainly trim the number of explorers and explain Hart's fact A. Or perhaps population growth is not, as many researchers have supposed, a strong motivation for voyaging to the stars, especially for a species that restrains any rapacious impulses and develops a truly sustainable existence in its home system. The ultimate green revolution would remove the impetus to go farther afield for anything other than scientific exploration.

Spreading across our galaxy need not require much more than persistence and a modest amount of cosmic time.

Sounding a more ominous note are concepts such as the "great filter"—the idea that there is something that always limits a species, perhaps an inevitable failure to achieve that green revolution, leading to an implosive extinction of all potentially technological life. Alternatively, maybe natural cataclysms, from supernovae explosions to outbursts from the Milky Way's central black hole, simply prune galactic life regularly enough to keep it from becoming widespread.

More outrageous proposals include the zoo hypothesis. In this scenario, we are being kept deliber-

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Alone in a Crowd

Of all possible answers to the question of why we have not seen other cosmic cultures in the Milky Way, perhaps the most plausible is that they exist but are not in our neighborhood. This situation could arise if interstellar exploration and migration are patchy and occur in waves, with spacefaring civilizations periodically expanding to settle the closest, choicest planetary systems. Accounting for stellar motions and a finite lifetime for each civilization, simulations of this process produce clusters of continuously occupied systems—as well as isolated, sparsely settled regions, one of which could harbor our own lonely world.

GALACTIC DIASPORAS

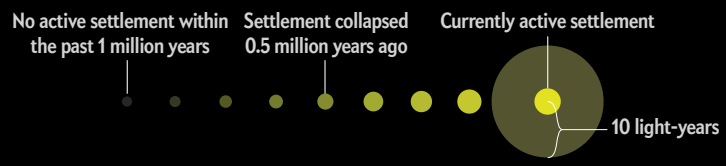
A snapshot from a simulation depicts 10 million years of interstellar exploration for 10,000 settleable systems within a box roughly 464 light-years on a side. (Systems unfit for settlement outnumber inviting systems by a factor of 22 but are not rendered here.) At this scale, stars move like particles in a gas, impeding or aiding interstellar travel via their trajectories with respect to one another. Probes originating from cultures scattered across this virtual space move at 3,000 kilometers per second—100 times faster than the average speed of surrounding stars, which follow a density distribution similar to that of our region of the galaxy.

● Each dot represents the current position of a settled or settleable planetary system.

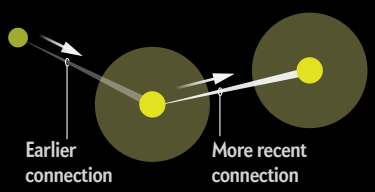
At the simulation's conclusion (*represented here*), 6,948 of the considered systems had been visited by a probe, but only 403 harbored active settlements; 3,052 settleable systems remained unvisited. This generated 11 distinct interstellar "empires" consisting of at least 10 settled systems, each denoted by a different color indicating common ancestry.

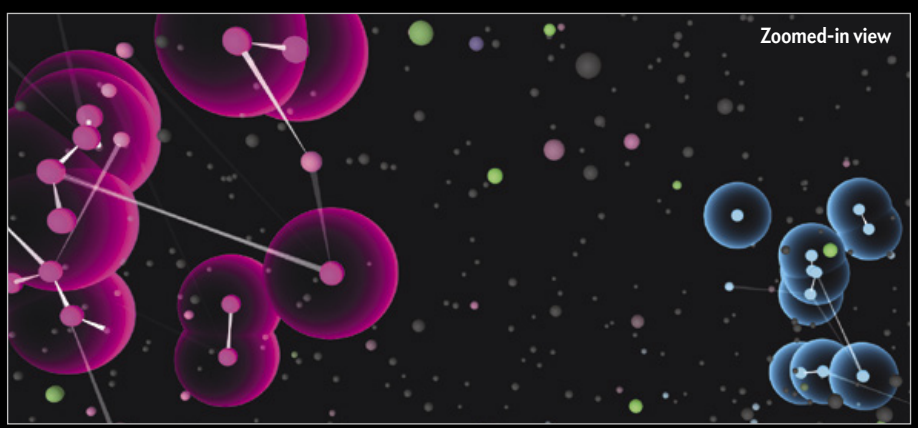
Additional settlement waves that settled fewer systems are depicted in gray.

Fading colors indicate systems that no longer harbor active settlements: currently active settlements are surrounded by semitransparent bubbles with radii of 10 light-years, demarcating the notional sphere of influence for any single system.


No active settlement within the past 1 million years
Settlement collapsed 0.5 million years ago
Currently active settlement
10 light-years

Agents targeted only systems within 10 light-years that could be settled, were not currently settled and were not targeted by another agent. Lines denote successful interstellar voyages and connect recently settled systems with their parents. Lines do not show the actual path traveled—the relative positions of systems are in constant flux, frozen here at the end of the simulation.





WHERE IS EARTH?

This simulation is a crude approximation of our galactic neighborhood. The solar system could reside within any unsettled portion of this box. Produced by statistical fluctuations in the trajectories and planetary architectures of surrounding stars, these transient "voids" are regions in which habitable worlds would lie beyond the reach of surrounding civilizations.

Source: Jonathan Carroll-Nellenback *University of Rochester*

Graphic by Nadieh Bremer

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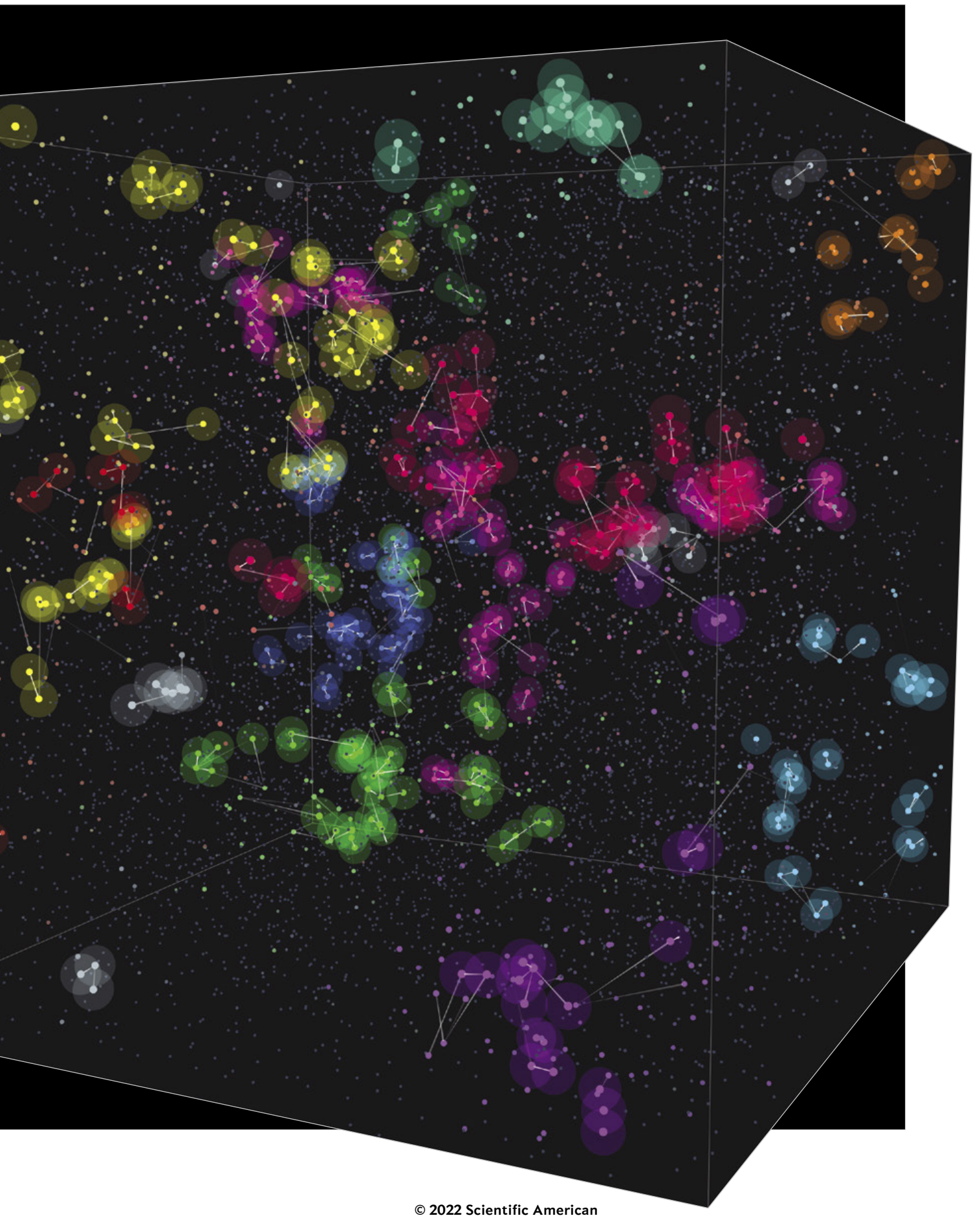

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ately isolated and in the dark by alien powers that be. There is also what I like to call the paranoia scenario: other civilizations are out there but are hiding from one another and refusing to communicate because of some kind of cosmic xenophobia.

Perhaps, though, there are simpler ways to explain our current ignorance about aliens. Those answers could share characteristics with the example right under our noses—the time-varying and patchy nature of human occupation in the islands of the South Pacific. In both terrestrial and extraterrestrial cases, there are basic, universal factors at play, from the scarcity of good places to drop anchor to the time it might take for a population to ready itself to push farther across the void.

BACK IN 2015 MY COLLEAGUE ADAM FRANK OF THE University of Rochester and I were having lunch near Columbia University's campus in New York City. As at Fermi's lunch 65 years earlier, the conversation was about the nature of spacefaring species. And inspired by Fermi's spur-of-the-moment mental calculation, we were trying to craft an investigative strategy that made the fewest possible unsubstantiated assumptions and that could be somehow tested or constrained with real data. At the center of this exercise was the simple thought that, just as with Pitcairn Island's transitory occupants, waves of exploration or settlement could come and go across the galaxy, with humans happening to emerge in one of the lonely periods.

Elsewhere in the galaxy there may be archipelagos of interstellar species for whom cosmic visitors are the norm.

This idea relates to Hart's original fact A: that there is no evidence here on Earth today of extraterrestrial explorers. But it goes further by asking whether we can obtain meaningful limits on galactic life by constraining the exact length of time over which Earth might have gone unvisited. Perhaps long, long ago aliens came and went. A number of scientists have, over the years, discussed the possibility of looking for artifacts that might have been left behind after such visitations of our solar system. The necessary scope of a complete search is hard to predict, but the situation on Earth alone turns out to be a bit more manageable. In 2018 another of my colleagues, Gavin Schmidt of the NASA Goddard Institute for Space Studies, together with Frank, produced a critical assessment of whether we could even tell if there had been an earlier industrial civilization on our planet.

As fantastic as it may seem, Schmidt and Frank argue—as do most planetary scientists—that it is actually very easy for time to erase essentially all signs of technological life on Earth. The only real evidence after a million or more years would boil down to isotopic or chemical stratigraphic anomalies—odd features such as synthetic molecules, plastics or radioactive fallout. Fossil remains and other paleontological markers are so rare and so contingent on special conditions of formation that they might not tell us anything in this case.

Indeed, modern human urbanization covers only on the order of about 1 percent of the planetary surface, providing a very small target area for any paleontologists in the distant future. Schmidt and Frank also conclude that nobody has yet performed the necessary experiments to look exhaustively for such nonnatural signatures on Earth. The bottom line is, if an industrial civilization on the scale of our own had existed a few million years ago, we might not know about it. That absolutely does not mean one existed; it indicates only that the possibility cannot be rigorously eliminated.

Over the past several years we have pursued the grander, galaxy-wide implications of these ideas in an investigation led by Jonathan Carroll-Nellenback of the University of Rochester and with Wright. A key advance has been the development of a series of agent-based computer simulations, backed up by old-fashioned paper-and-pencil mathematics, which has enabled us to build a more realistic picture of how species might move around in a galaxy that is itself full of motion.

If you take a snapshot of stars within a couple of hundred light-years of the sun, you will find that they are moving like the particles in a gas. Relative to any fixed point in this space, a star may be moving rapidly or slowly and in what is effectively a random direction. Zoom out farther, to scales of thousands of light-years, and you will begin to register the grand, shared orbital motion that carries a star such as our sun around the Milky Way once every 230 million years or so. Stars much closer to the galactic center take much less time to complete a circuit, and there are fast-moving "halo" stars diving in and out of the plane of the galactic disk as part of a distinct, rather spherically shaped swarm surrounding that disk.

What this means is that for a civilization looking around itself for target stars to explore, what is closest and what will be closest in the future vary significantly over time. A good illustration of this is our own solar system. Right now our nearest star, Proxima Centauri, is 4.24 light-years away, but in about 10,000 years it will be only 3.5 light-years distant—a significant savings in interstellar travel time. If we were to wait until about 37,000 years from today, our nearest neighbor would for a time be a small red dwarf star called Ross 248, which would then be a mere three light-years from us.

To model this shifting stellar map, our simulation uses a three-dimensional box of stars, with move-

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ments akin to those in a small part of a real galaxy. It then initiates a "front" of settlement by assigning a selection of those stars as hosts to spacefaring civilizations. Those civilizations have finite life spans, so a system can also become unoccupied. And a civilization has a waiting period before it is capable of launching a probe or settlement effort to its nearest neighboring star. All these factors can be altered, tweaked and explored to see how they affect the outcome. For a wide range of possibilities, a somewhat raggedy-looking settlement front self-propagates through interstellar space. The speed of this propagating front is the key to cross-checking and confirming possible solutions to Fermi's original puzzle.

What we find is both simple and subtle. First, the natural, gaslike motion of stars in the galaxy means that even the slowest interstellar probes, moving at some 30 kilometers per second (nearly twice as fast as Voyager 1's current speed of 17 kilometers per second in its outbound motion from our sun), would ensure that a settlement front would cross the galaxy in much less than a billion years. If we factor in other stellar motions, from galactic rotation or halo stars, this time span only shrinks. In other words, just as Fermi saw, it is not hard to fill the galaxy with life. But it is also the case that exactly how "filled" the galaxy becomes depends on both the number of genuinely settleable worlds out there—what we have dubbed the Aurora effect in homage to Kim Stanley Robinson's epic 2015 science-fiction novel *Aurora*—and the length of the period civilizations are able to endure on a world.

At one extreme, it is easy to make the galaxy empty by simply shrinking the number of usable planets and having civilizations last for only, say, 100,000 years or so. At the other extreme, it is easy to tweak these factors to fill space with active spacefaring settlements. In fact, if suitable worlds are numerous enough, it almost does not matter how long settled civilizations last on average. If they retain the technology that allowed them to travel in the first place, then enough of them could carry on exploring and eventually fill the galaxy.

But it is between these extremes that the most compelling and potentially realistic situations arise. When the frequency of occurrence of settleable worlds in a galaxy is intermediate between high and very low, fascinating things can happen. Specifically, ordinary statistical fluctuations in the number and location of suitable worlds in patches of galactic space can create clusters of systems that are continually visited or resettled by wave after wave of interstellar explorers. Think of it as an archipelago, a group or chain of islands. The flip side to the existence of these clusters is that they are typically surrounded by large unsettled regions of space, places just too far and too sparsely distributed to bother setting out for.

CAN THIS "GALACTIC ARCHIPELAGO" SCENARIO explain our situation on Earth? Remarkably, it may. For example, if typical planetary civilizations can last for a million years and if only 3 percent of star systems are actually settleable, there is a roughly 10 percent probability that a planet like Earth has not been visited in at least the past million years. In other words, it is not terribly unlikely that we would find ourselves on the lonely side of the equation.

Conversely, this scenario implies that elsewhere in the galaxy there are clusters, archipelagos, of interstellar species for whom cosmic neighbors or visitors are the norm. No extreme hypotheses are needed for any of this to take place; it would require just a rather ordinary accounting of planetary numbers and the nature of stellar movements amid the swirling stars of the Milky Way. And although it is true that assumptions linger about the feasibility of any kind of interstellar travel and about the likelihood that a species will actually undertake it, other factors are just parameters to be tuned. Some, such as the number of inhabitable worlds, are in astronomers' sights already as we seek greater knowledge of exoplanets. Others, such as the longevity of civilizations, are the subject of intense scrutiny as we attempt to deal with our own issues of planetary sustainability.

The possibility also exists for us to discover evidence of settled stellar archipelagos or the ongoing propagation of a settlement front. Targeting our searches for extraterrestrial intelligence and technology not on individual, known exoplanets but rather on galactic regions where the topography of stars might lend itself to interstellar expansion or clustering could be an interesting new strategy. Until recently, our three-dimensional map of galactic space was woefully limited, but with instruments such as the European Space Agency's Gaia observatory mapping a billion astronomical objects and stellar motions, we might be able to chart these hotspots.

In the end, though, the true paradox of Fermi's paradox may be that there is no paradox at all. What my colleagues' work shows is that it is an entirely natural state for a habitable, inhabited world such as Earth to exhibit no discernible evidence of having ever been visited or settled by an extraterrestrial species. This is true whether the galaxy is devoid of other technologically advanced life or is as teeming as it can be with interstellar explorers. Just as Pitcairn may have sat unoccupied for as much as three centuries in the Pacific Ocean, Earth might simply be passing through a period of isolation before the cosmic ripple of pan-galactic life washes over it once again.

The real question, as it was for Polynesian settlers across the centuries, is whether our planetary civilization will still be here when that happens. SA

Caleb Scharf is director of the Columbia Astrobiology Center and author of several books, including *The Copernicus Complex* (2014) and *The Zoomable Universe* (2017). He wrote the Life, Unbounded blog for *Scientific American* and has written for many other publications. Scharf lives in New York City with his wife and two daughters.

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Alone in the Milky Way

Why we are probably the only intelligent life in the galaxy

By John Gribbin

Illustration by Armando Veve

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ASTRONOMERS HAVE NOW FOUND THOUSANDS OF PLANETS ORBITING other stars in the Milky Way, and 100 billion more stars in the galaxy presumably host planets of their own. Given the sheer number of worlds out there, scientists find it easy to hope that some of them must be harboring sentient beings. After all, could Earth really be unique among so many planets?

It could. Optimism about the possibilities of intelligent extraterrestrial life ignores what we know about how humans came to exist. We are here because of a long chain of implausible coincidences—many, many, many things had to go right to result in the situation in which we find ourselves. This chain is so implausible, in fact, that there is good reason to conclude that humans most likely are the only technological civilization in the galaxy. (Let us leave aside the other countless galaxies in the cosmos because, as the saying has it, "in an infinite universe, anything is possible.")

SPECIAL TIMING

THE COINCIDENCES BEGIN with the manufacture of heavy elements, which include everything heavier than hydrogen and helium. The first stars were born in clouds of these two lightest elements, the residue of the big bang, more than 13 billion years ago. They cannot have had planets, because there was nothing to make planets from—no carbon, oxygen, silicon, iron or any other metals (with cavalier disregard for chemical subtleties, astronomers call all elements heavier than hydrogen and helium metals).

Metals are created inside stars and spread through space when stars throw off material as they die, sometimes in spectacular supernova explosions. This material enriches interstellar clouds, so each successive generation of stars made from the clouds will have a greater metallicity than the one before it. When the sun came into being about 4.5 billion years ago, this enrichment had been going on for billions of years in our galactic neighborhood. Even so, the sun contains roughly 71 percent hydrogen, 27 percent helium and just 2 percent metals. Its composition mirrors that of the cloud that made the solar system, so the rocky planets, including Earth, formed from only that tiny amount of elemental construction material. Stars older than the sun have even fewer metals and, correspondingly, less chance of making rocky, Earth-like planets (giant gaseous planets, such as Jupiter, are easier to form but not as likely to host life). This means

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Chain of Improbable Coincidences

Many things had to go right for us to exist. Serendipity in the timing and location of our home star and planet, as well as lucky conditions on Earth and fortuitous developments in the evolution of life, resulted in human beings.

Timing

If the sun and Earth had been born any earlier in galactic history, our planet would likely have had too few metals (elements heavier than hydrogen or helium) to form life. These elements are created during stellar deaths, and it took billions of years for enough stars to form and die to enrich the materials that built our solar system.

Location

The sun lies in a Goldilocks zone within the Milky Way—not too close to the galactic center, where stars are more crowded and dangerous events such as supernovae and gamma-ray bursts are common, and not too far, where stars are too sparse for enough metals to build up to form rocky planets.

Planetary Conditions

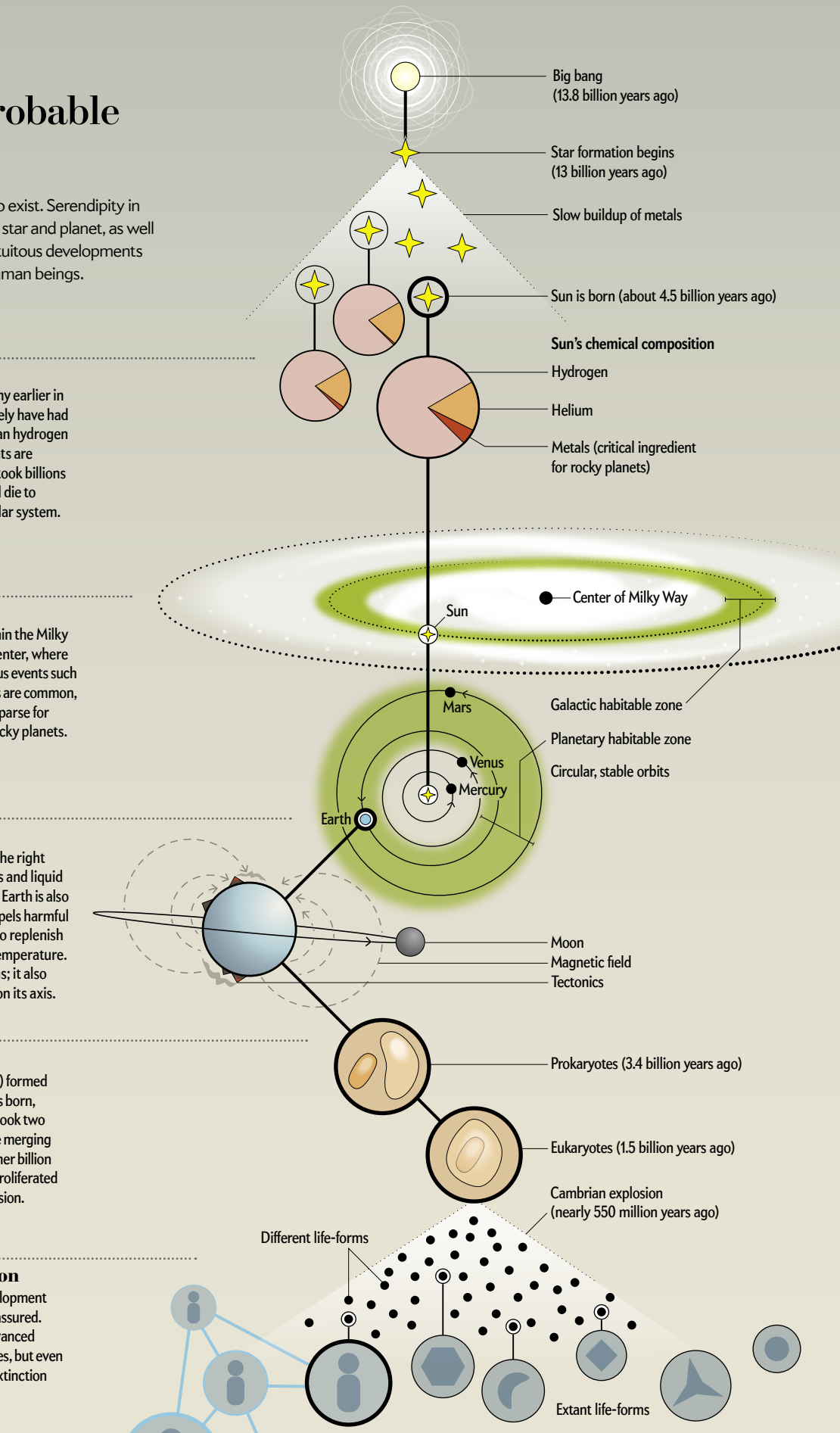
Within our solar system, Earth is in the right location for hospitable temperatures and liquid water (the planetary habitable zone). Earth is also lucky to have a magnetic field that repels harmful radiation, as well as plate tectonics to replenish surface nutrients and stabilize the temperature. Our moon is likely behind both boons; it also prevents Earth from tipping too far on its axis.

Early Life

Single-celled organisms (prokaryotes) formed just a billion years after our planet was born, but more complex cells (eukaryotes) took two billion years more to arise from a fluke merging of cells. Even then, it was almost another billion years before multicellular life-forms proliferated in an event called the Cambrian explosion.

Technological Civilization

Once multicellular life arose, the development of an intelligent species was far from assured. We still do not know how humans advanced so far beyond our close animal relatives, but even our species may have come close to extinction several times, DNA evidence shows.



Graphic by Jen Christiansen

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that even if we are not the only technological civilization in the galaxy, we must be one of the first.

SPECIAL LOCATION

OUR PLACE IN THE MILKY WAY is also propitious. The sun is located in a thin disk of stars about 100,000 light-years across; it is roughly 27,000 light-years from the galactic center, a little more than halfway to the rim. By and large, stars closer to the center contain more metals, and there are more old stars there. This situation is typical of disk galaxies, which seem to have grown outward from the center.

More metals sounds like a good thing from the point of view of making rocky planets, but it may not be so good for life. One reason for the extra metallicity is that stars are packed more densely toward the center, so there are many supernovae, which produce energetic radiation—x-rays and charged particles known as cosmic rays—that is harmful to planets of nearby stars. The galactic center also is home to a very large black hole, Sagittarius A*, which produces intense outbursts of radiation from time to time.

Then there is the problem of even more energetic events called gamma-ray bursts. Using gravitational-wave studies, astronomers learned that some of these explosions are caused by merging neutron stars. Observations of gamma-ray bursts in other galaxies show that they are more common in the crowded inner regions of galaxies. A single burst could sterilize the core of the Milky Way, and statistics based on studies of other galaxies suggest that one occurs in ours every one million to 100 million years.

Farther from the center, all these catastrophic events have less impact, but stars are sparser and metallicity is lower, so there are fewer rocky planets, if any. Taking everything into account, astronomers such as Charles H. Lineweaver of the Australian National University infer that there is a "galactic habitable zone" extending from about 23,000 to 30,000 light-years from the galactic center—only about 7 percent of the galactic radius, containing fewer than 5 percent of the stars because of the way they are concentrated toward the core. That region still encompasses a lot of stars but rules out life for the majority of them in our galaxy.

The sun is close to the middle of the habitable zone, but other astronomical idiosyncrasies distinguish our solar system. For example, there is some evidence that an orderly arrangement of planets in nearly circular orbits providing long-term stability is uncommon, and most planetary systems are chaotic places, lacking the calm Earth has provided for life to evolve.

SPECIAL PLANET

ALL THE TALK OF EARTH-LIKE PLANETS obscures another critical distinction. Astronomers have found many such worlds, but when they say "Earth-like planet," all they mean is a rocky planet in the habitable zone that is about the same size as ours. By this criterion, the most Earth-like planet we know is Venus—but you could never live there. The fact that you can live on Earth is the result of fortuitous circumstances.

The two planets differ in several important ways. Venus has a thick crust, no sign of plate tectonics and essentially no magnetic field. Earth has a thin, mobile crust where tectonic activity, especially around plate boundaries, brings material to the surface through volcanism. Over Earth's long history, this activity has carried ores up to where humans can mine them to provide the raw materials for our technological civilization. Plate tectonics has also brought nutrients to the surface to replenish those that get depleted by the cells living there, and it is crucial for recycling carbon and stabilizing the temperature over long timescales. Earth also has a large metallic (in the everyday sense of the word) core that, coupled with its rapid rotation, produces a strong magnetic field to shield its surface from harmful cosmic radiation. Without this screen, our atmosphere would probably erode, and any living thing on the surface would get fried.

All these attributes of our planet are directly related to our moon—another feature that Venus and many other Earth-like planets lack. Scientists' best guess is that the moon formed early in the solar system's history, when a Mars-size object struck the nascent Earth a glancing blow that caused both protoplanets to melt. The metallic material from the two objects settled into Earth's center, and much of our planet's original lighter rocky material splashed out to become the moon, leaving Earth with a thinner crust than before. Without that impact, Earth would be a sterile lump of rock like Venus, lacking a magnetic field and plate tectonics. The presence of such a large moon has also acted as a stabilizer for our planet. Over the millennia Earth has wobbled on its axis as it has gone around the sun, but thanks to the gravitational influence of the moon, it can never topple far from the vertical, as seems to have happened with Mars. It is impossible to say how often such impacts occur to form double systems such as Earth and its moon. But clearly, they are rare, and without our satellite we would likely not be here.

SPECIAL LIFE

ONCE THE EARTH-MOON SYSTEM settled down, life emerged with almost indecent rapidity. Leaving aside controversial claims for evidence of even earlier creatures, scientists have found fossil remains of single-celled organisms in rocks 3.4 billion years old—just about a billion years younger than Earth itself. At first, this sounds like good news for anyone hoping to find extraterrestrials—surely if life got started on Earth so soon, it could arise with equal ease on other planets? The snag is that although it started, it did not do much for the next three billion years. Indeed, microbes that are essentially identical to those origi-

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nal bacterial cells still live on Earth today—arguably the most successful species in the history of life on our planet and a classic example of "if it ain't broke, don't fix it."

These simple cells, known as prokaryotes, are little more than bags of jelly, containing the basic molecules of life (such as DNA) but without the central nucleus and specialized structures such as mitochondria, which use chemical reactions to generate the energy needed by the cells in your body. The more complex cells, the stuff of animals and plants, are known as eukaryotes, and they are all descended from a single merging of cells that occurred about 1.5 billion years ago.

The merger involved two types of primordial single-celled organisms: bacteria and archaea. The latter are so named because they were once thought to be older than bacteria. The evidence now suggests that both forms emerged at about the same time, when life first appeared on Earth—meaning that however life got started, it actually emerged twice. Once it was here, it went about its business largely unchanged for about two billion years. That business involved, among other things, "eating" other prokaryotes by engulfing them and using their raw materials.

Then came the dramatic turning point: An archaeon engulfed a bacterium but did not "digest" it. The bacterium became a resident of the new cell, the first eukaryote, and evolved to carry out specialized duties within it, leaving the rest of the host free to develop without worrying about where it got its energy. The cell then repeated the trick, becoming more complex.

The similarities between the cells of all advanced life-forms on Earth show that they are descended from a *single* single-celled ancestor—as biologists are fond of saying, at the level of a cell there is no difference between you and a mushroom. Of course, the trick might have happened more than once, but if it did, the other protoeukaryotes left no descendants (probably because they got eaten). It is a measure of how unlikely such a single fusion of cells was that it took two billion years of evolution to occur.

Even then, not much happened for another billion years or so. Early eukaryotes got together to make multicellular organisms, but at first these were nothing more than flat, soft-bodied creatures resembling the structure of a quilt. The proliferation of multicellular life-forms that led to the variety of life on Earth today kicked off only about 550 million years ago, in an outburst known as the Cambrian explosion. This was such a spectacular event that it is still the most significant one in the fossil record. But nobody knows why it happened—or how likely it is to happen elsewhere. Eventually that eruption of life produced a species capable of developing technology and wondering where it came from.

SPECIAL SPECIES

THE PROGRESSION from primitive to advanced species was not easy. The history of humanity is written in our genes, in such detail that it is possible to determine from DNA analysis not only where different populations came from but how many of them were around. One of the surprising conclusions from this kind of analysis is that groups of chimpanzees living close to one another in central Africa are more different genetically than humans living on opposite sides of the world. This can only mean that we are all descended from a tiny population of humans, possibly the survivors of some catastrophe or catastrophes.

Even if we are not the only technological civilization in the galaxy, we must be one of the first. Is another such civilization likely to exist today? Almost certainly no. We are unique in the whole Milky Way.

DNA evidence pinpoints two evolutionary bottlenecks in particular. A little more than 150,000 years ago the human population was reduced to no more than a few thousand—perhaps only a few hundred—breeding pairs. And about 70,000 years ago the entire human population fell to about 1,000. Although this interpretation of the evidence has been questioned by some researchers, if it is correct, all the billions of people now on Earth are descended from this group, which was so small that a species diminished to such numbers today would likely be regarded as endangered.

That our species survived—and even flourished, eventually growing to number nearly eight billion and advancing into a technological society—is amazing. This outcome seems far from assured.

As we put everything together, what can we say? Is life likely to exist elsewhere in the galaxy? Almost certainly yes, given the speed with which it appeared on Earth. Is another technological civilization likely to exist today? Almost certainly no, given the chain of circumstances that led to our existence. These considerations suggest we are unique not just on our planet but in the whole Milky Way. And if our planet is so special, it becomes all the more important to preserve this unique world for ourselves, our descendants and the many creatures that call Earth home. SA

John Gribbin is a science writer, an astrophysicist and a visiting fellow in astronomy at the University of Sussex in England. He is author of *Alone in the Universe* (Wiley, 2011).

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END NOTE

We Are the Aliens

The emergence of the human "dataome" is like a sudden invasion of Earth

By Caleb Scharf

***Something very old,** very powerful and very special has been unleashed on Earth.*

Humans are strange. For a global species, we're not particularly genetically diverse, thanks in part to how our ancient roaming explorations caused "founder effects" and "bottleneck events" that restricted our ancestral gene pool. We also have a truly outsize impact on the planetary environment without much in the way of natural attrition to trim our influence (at least not yet).

But the strangest thing of all is how we generate, exploit and propagate information that is not encoded in our heritable genetic material yet travels with us through time and space. Not only is much of that information represented purely symbolically—in alphabets, languages, binary codes—it also is represented in each brick, alloy, machine and structure we build from the materials around us. Even the symbolic stuff is instantiated in some material form or other, whether as ink on pages or electrical charges in nanoscale pieces of silicon.

Altogether, this "dataome" has become an integral part of our existence. In fact, it may have been an integral, and essential, part of our existence since our species of hominins became more and more distinct some 200,000 years ago. This idea, which I also pursue in my book *The Ascent of Information,* leads to a number of quite startling and provocative proposals.

To begin with, we can look at our species' energy use and see that of the roughly six to seven terawatts of average global electricity production, about 3 to 4 percent is gobbled up by our digital electronics, in computing, storing and moving information. That might not sound too bad—except the growth trend of our digitized informational world is such that it requires approximately 40 percent more power every year. Even allowing for improvements in computational efficiency and power generation, this points to a world in some 20 years where all of the energy we now generate in electricity will be consumed by digital information alone.

The energy tsunami of the human dataome doesn't end there. We still print onto paper, and the energy cost of a single page is the equivalent of burning five grams of high-quality coal. Devices, from microprocessors to hard drives, are also extraordinarily demanding in terms of their production. We literally fight against the second law of thermodynamics to forge these exquisitely ordered, low-entropy structures out of raw materials that are decidedly high entropy in their messy natural states.

All of which raises the question: Why exactly are we doing this?

An unexpected answer is that it's not just us doing this. Our dataome is startlingly like a symbiotic organism. *Homo sapiens* arguably exists only because of our species' coevolution with this wealth of externalized information: from languages held only in neuronal structures across many generations to our tools and our creations on pottery and cave walls, all the way to today's online world.

But symbiosis also implies that all parties may have selfish interests. This opens the door to asking whether we're calling all the shots. After all, in a gene-centered view of biology, all living things are simply temporary vehicles for the propagation and survival of information. In that sense, the dataome is no different, and exactly how information survives is less important than the fact that it can do so. Once that information and its algorithmic underpinnings are in place in the world, the dataome will keep going forever if it can.

A very simple example can be seen in any of the great works of human literature, from Lao Tzu to Shakespeare. These informational packages have found a way to persist through time by attaching themselves to us. We eagerly read them, restructuring our brains to remember them, and we go to great lengths to copy and reproduce these works again and again across the centuries and in many languages and forms. But these texts aren't just memes; they're more like an extension of the human phenotype that has its own processes and its own capacity to pressure the world around it to try to ensure its survival.

Throughout life's three- to four-billion-year history on Earth, it doesn't seem that anything exactly like this has happened before. On a geologic timescale, the emergence of the human dataome is like a sudden alien invasion or an asteroid impact—changing how the biosphere functions. It's not just flesh-and-blood life on this world anymore. By a quirk of evolution, our very existence has unleashed a new trick for the restructuring of matter in service of entropy and its cousin, information.

Look around where you are right now, at the walls of your room or the chair you're sitting on. Or the light you're reading by and the screen or paper you're reading these words from. In the end, all these things are here in support of data, of ideas and of the most potent quantity in the universe: information. Our very alien dataome may just be the harbinger of things to come. SA

Caleb Scharf is director of the Columbia Astrobiology Center and author of several books, including *The Copernicus Complex* (2014) and *The Zoomable Universe* (2017). He wrote the Life, Unbounded blog for *Scientific American* and has written for many other publications. Scharf lives in New York City with his wife and two daughters.

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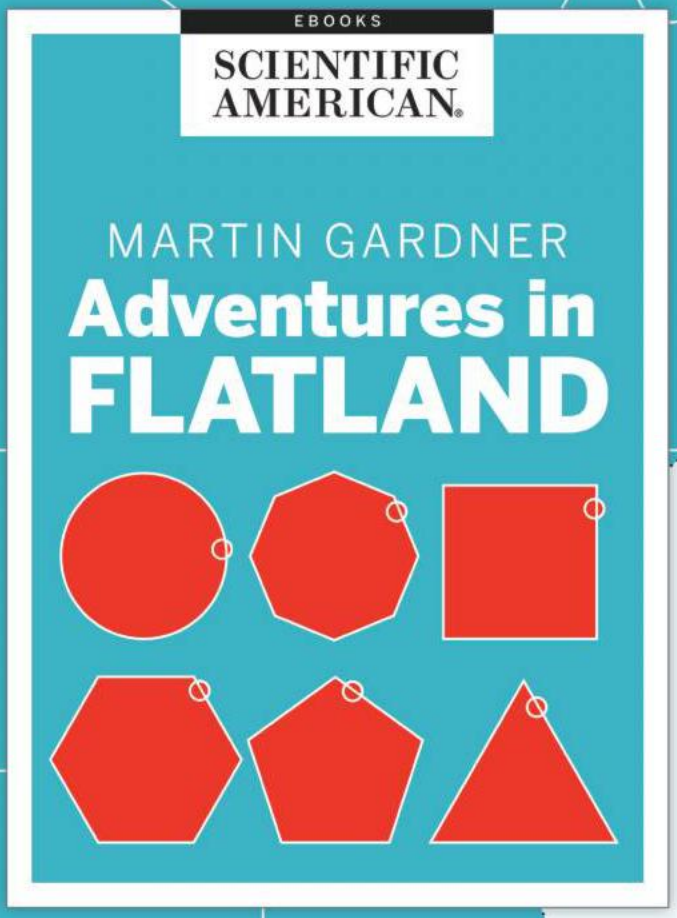

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